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FINAL PROJECT REPORT  
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PART I—PROJECT IDENTIFICATION INFORMATION

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	4. Award Period From 5/1/86 To 2/28/87	5. Cumulative Award Amount \$17,568.36
6. Project Title Knowledge-Based Expert Systems and Robotics		

PART II—SUMMARY OF COMPLETED PROJECT (FOR PUBLIC USE)

Two economic feasibility models were developed for robotics application in construction industry: 1) Economic feasibility rating of robotics; (2) Economic feasibility of robotics by knowledge-based expert system. The first model considers three main factors: a) productivity improvement; (b) quality improvement; and c) saving in skilled labor. In this method, the construction processes are compared with each other, and economic rating values are implemented. A discussion of rationale used to assign the ratings for fire proofing spray operation is presented. The second economic feasibility model is developed based on knowledge-based expert systems. The research in this part consisted of three stages. In stage one, a general inference net was developed. Diversifying a little from the above beginning stage, a second stage was developed by separately analyzing any aspect affecting the feasibility study. In stage three some modifications were made to simplify the inference net. A prototype microcomputer knowledge-based system was developed. The program presents a list of construction processes appropriate for robotization, and describes their characteristics. The knowledge-based system can assist contractors at the beginning stage to get the state of the art knowledge about construction robotization, and perform an overall feasibility analysis.

PART III—TECHNICAL INFORMATION (FOR PROGRAM MANAGEMENT USES)

1. ITEM (Check appropriate blocks)	NONE	ATTACHED	PREVIOUSLY FURNISHED	TO BE FURNISHED SEPARATELY TO PROGRAM	
				Check (✓)	Approx. Date
a. Abstracts of Theses					
b. Publication Citations					
c. Data on Scientific Collaborators					
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e. Technical Description of Project and Results					
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2. Principal Investigator/Project Director Name (Typed) Roozbeh Kangari		3. Principal Investigator/Project Director Signature		4. Date 9/15/87	

**FINAL RESEARCH PROJECT REPORT**

**TO:** *Office of Contract Administration  
University of Maryland  
College Park, Maryland 20742*

**FROM:** *Roozbeh Kangari  
School of Civil Engineering  
Georgia Institute of Technology  
Atlanta, GA 30332*

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**ATTENTION OF:** *Dr. Dan Halpin  
Civil Engineering Department  
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## **CHAPTER 12**

### **ECONOMIC FEASIBILITY MODELS**

Two economic feasibility models were developed for robotics application in construction Industry: 1) Economic feasibility rating of robotics; and 2) Economic feasibility of robotics by knowledge-based expert system.

#### **ECONOMIC FEASIBILITY RATING ANALYSIS**

Economic benefits of automation and robotization in construction are basically due to:

a) productivity improvement; b) quality improvement; and c) saving in skilled labor. In this part, a methodology for economic analysis of construction process automation based on economic feasibility rating will be presented.

The first main factor in economic analysis is productivity improvement. Productivity can simply be defined as the ratio of output to input, typically given as units produced per man-hours required. A comparison between productivity of the current system and the proposed robotic system should be made. If historical data on productivity is not available then a study to determine these values must be made. If a construction operation is automated or robotized, it is expected to have an increase in productivity to absorb the cost incurred in robot implementation. Obviously, productivity improvement is not the only factor that pays for the robot.

The second factor that must be considered in economic analysis is quality improvement. Quality improvement is one major reason for the implementation of robot to produce a better quality compared to traditional systems. Quality of a construction product can be measured by a numerical model which considers such characteristics as strength, dimension, color, and etc. Only the relevant characteristics of an operation product should be considered. There is a direct correlation between cost and level of quality improved.

The third factor is saving in labor cost. Saving in skilled labor is a prime issue in justifying a

robot in a long term planning. The key motivator in future for construction robotization is the saving of labor cost by supplanting a human worker with a labor. High and rising labor cost can be expected to accelerate the utilization of labor saving technology in general, and automation in particular. However, many of intangible indirect costs associated with bring a robot on construction site and maintaining it are often overlooked.

To develop a rating system for numerical evaluation, a table with thirty-three construction processes is developed as shown in Table 12.1. In this table, the construction processes are compared with each other, and an economic rating values based on one to ten scale is implemented as described in technological feasibility section.

In this method, each construction process is rated for the three economic factors. A rating of one to ten is assigned for each economic factor. High numbers correspond to a high level of economic benefit for automation in that category. Then, the assigned rating values are multiplied by weight factors in each category. Higher weight factors indicate the importance of the category. Table 12.1 represents an example of this rating system. A discussion of the rationale used to assign the ratings for fireproofing (spray) is provided below.

#### **ECONOMIC FEASIBILITY RATING FOR FIREPROOFING SPRAY**

To further describe this model, fireproofing operation is selected to demonstrate the concept. Fireproofing cover material for steel is required to keep strength of steel structure during fire. One process of fireproofing is to use a solid board, the other is to spray fireproofing materials. There are three processing methods used: dry; wet; and semi-dry.

The spraying of fireproofing material is carried out by construction workers on site. Rolling tower for scaffolding is used. The worker on the scaffolding have to wave the spray nozzle. The working environment is quite bad with small particles of rock wool filling surrounding area. Since

Feasability Of Automation Of Selected Construction Processes  
Based On Economic Feasability

\*\*\*\*\*

Economic Impact of Automation

WHAT ARE THE ECONOMIC BENEFITS , IN CASE OF AUTOMATION  
ASSOCIATED WITH THE FOLLOWING CHANGES:

	*PRODUCTIVITY *IMPROVEMENT	*QUALITY *IMPROVEMENT	* SAVING IN *SKILLED LABOR	*TOTAL*
Weight Factor	* 0.30	* 0.30	* 0.40	* 1.00*
Construction Process	*	*	*	*
*****	*	*	*	*
Bush Hammering	* 7	* 4	* 9	* 6.9 *
Concrete Placement	* 9	* 9	* 8	* 8.6 *
Crane Operations	* 8	* 4	* 8	* 6.8 *
Decking	* 6	* 6	* 8	* 6.8 *
Ditching	* 9	* 4	* 6	* 6.3 *
Drywall	* 9	* 8	* 7	* 7.9 *
Ductwork	* 7	* 7	* 8	* 7.4 *
Fireproofing (spray)	* 9	* 9	* 7	* 8.2 *
Formwork	* 8	* 8	* 7	* 7.6 *
Grading	* 9	* 4	* 5	* 5.9 *
Insulation (Siding)	* 8	* 8	* 9	* 8.4 *
Layout/Survey	* 6	* 3	* 6	* 5.1 *
Masonry	* 7	* 7	* 9	* 7.8 *
Painting	* 9	* 9	* 8	* 8.6 *
Pile Driving	* 8	* 6	* 6	* 6.6 *
Piping, Plumbing	* 9	* 8	* 8	* 8.3 *
Piping, Underground	* 8	* 8	* 9	* 8.4 *
Post-Tensioning	* 6	* 7	* 6	* 6.3 *
Precast, Cladding	* 7	* 7	* 8	* 7.4 *
Precast, Structural	* 7	* 7	* 8	* 7.4 *
Rebar Placement	* 8	* 8	* 9	* 8.4 *
Sandblasting	* 9	* 8	* 8	* 8.3 *
Scaffolding	* 7	* 6	* 7	* 6.7 *
Slurry walls	* 7	* 7	* 8	* 7.4 *
Sprinkler Piping	* 7	* 8	* 9	* 8.1 *
Steel , Fabrication	* 8	* 8	* 9	* 8.4 *
Steel, Structural	* 8	* 8	* 9	* 8.4 *
Tiling	* 9	* 9	* 8	* 8.6 *
Tunneling (Cast)	* 9	* 8	* 6	* 7.5 *
Tunneling (Cut/Muck)	* 9	* 8	* 6	* 7.5 *
Tunneling (Hand)	* 9	* 8	* 6	* 7.5 *
Tunneling (Precast)	* 8	* 8	* 6	* 7.2 *
Wall Finishing	* 7	* 9	* 9	* 8.4 *
*****				

TABLE 12.1 Economic Feasibility Analysis

fireproofing has a high impact on working environment and involves the repetition of spray motion, it is a job well suitable for a robot.

Implementing such a robot can improve the productivity for fireproofing operation. An economic rating of 9 has been assigned. The automation is also expected to improve quality of fireproofing when it is compared to manual operation. A rating of 9 justifies this requirement. This process requires a high skilled labor, and automation can save in skilled labor costs. The process gets a rating of 7 on a 10 point scale.

The assigned values are then multiplied by weight factors. As shown in the table, weight factors of 30%, 30%, and 40% are assigned to productivity, quality, and labor saving factors. A total rate of 8.2 is evaluated for this construction process for economic justification.

#### **MODELING FEASIBILITY OF ROBOTICS BY KNOWLEDGE-BASED SYSTEMS**

The second feasibility model is developed based on knowledge-based expert system. The main reason for implementing knowledge-based systems was that feasibility analysis of robotics in construction is a heuristic problem in general which requires experts knowledge. Knowledge-Based Expert Systems (KBES) are computer programs that use expert knowledge to attain high levels of performance in a narrow problem area. These programs typically represent knowledge symbolically, examine and explain their reasoning processes, and address problem areas that require years of special training and education for humans to master.

At the first stage of modeling, major factors in robotization of construction operations were identified. These factors were explored and relation between them was studied. At the second stage, the concepts and relationships for the knowledge-base were articulated. Patterns and strategies were studied. The objectives of this part were:

- a) to construct a knowledge-based expert system program that could provide a means for feasibility analysis of robotics application in construction at the present state of building and robotics technology,



- b) to specify robot requirements necessary to carry out the tasks that can be robotized, and
- c) to develop a base for utility analysis of feasibility of robotics in construction.

Next, the key concepts and information flow characteristics were developed in more formal patterns. Our basic sources of information were books, technical papers, as well as professional and expert views. The available state-of-the-art information about robotics in construction were organized in terms of certain hypothesized relationships.

### **Implementation**

The research in this part went through three evolutionary stages in effort to eliminate the difficulties and pitfalls and to augment the benefits resulting from the work.

#### **a) Stage One**

At the beginning stage a general inference net was developed. Figure 12.1 shows the flow of information in the knowledge base. This approach focused on three basic elements:

1) qualifications; 2) economic analysis; and 3) technological capability. This preliminary analysis presented a guideline which provided the necessary information to understand the basic principles of robotics application in construction.

#### **b) Stage Two**

Diversifying a little from the above beginning stage a second stage was developed and built upon the inference net representing expert systems program, as shown in Figure 12.2. During this stage attempt was made to approach the problem by separately analyzing any aspect affecting the feasibility study as follows:

1. State of technology: To build a data base containing information on various manipulators, sensors, mobility and control systems, as well as appropriate assemblers.
2. Union problems: Evaluate and quantify the problems, if any, that might appear in union works.

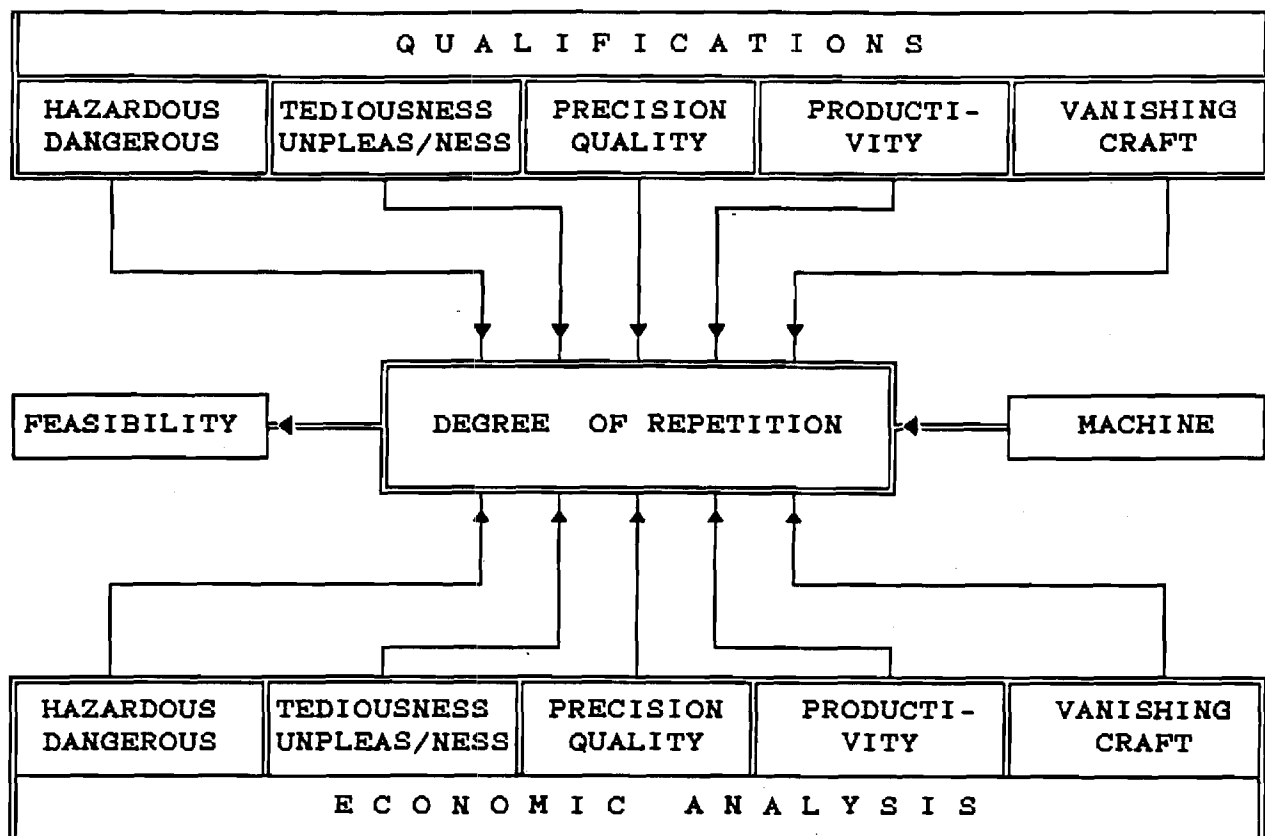
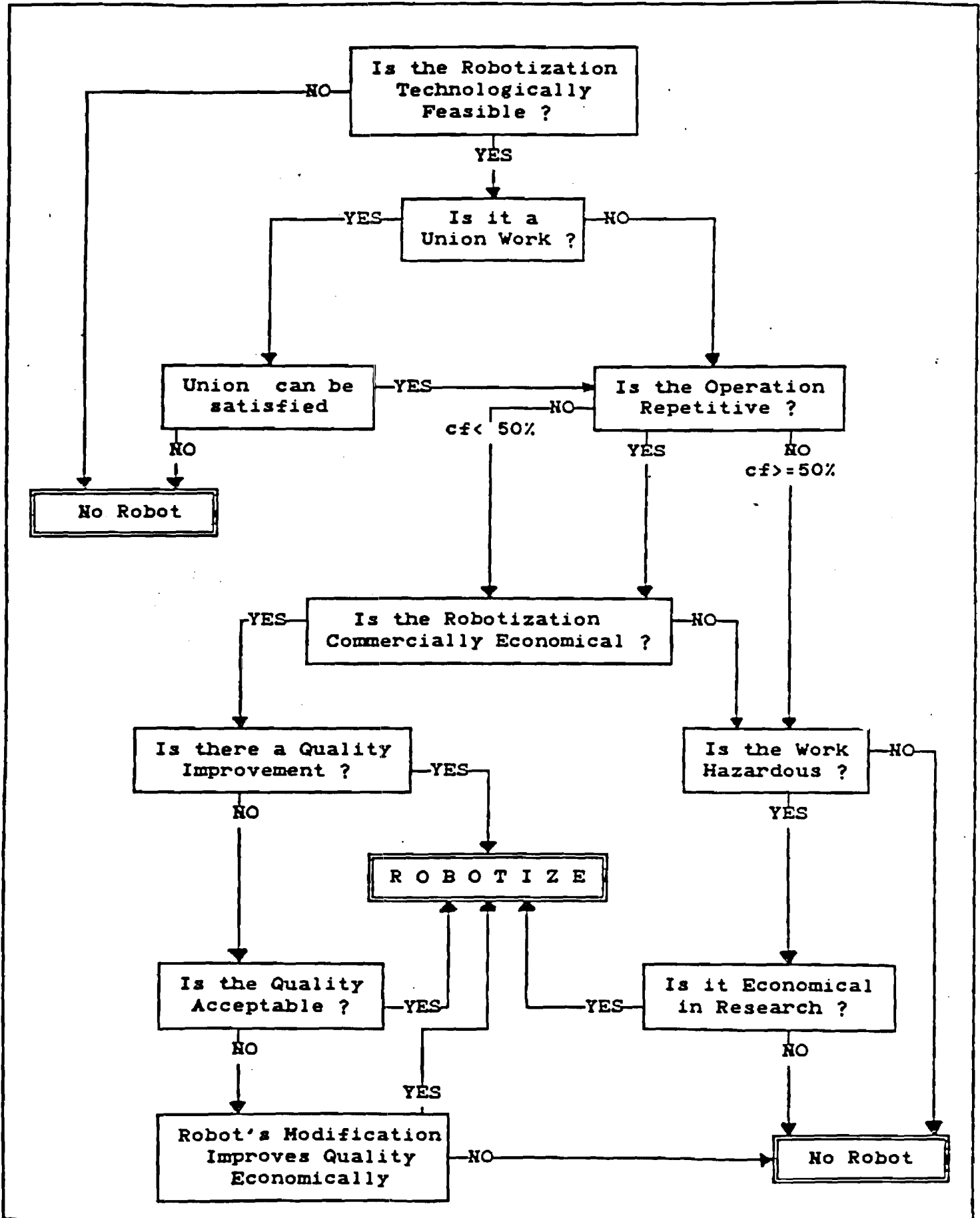


FIGURE 12.1 Aspects Affecting Feasibility Analysis (Stage 1)

FIGURE 12.2 Knowledge-Based Feasibility Analysis Of Robotization



3. Repetitiveness: Measure and evaluate the degree of repetitiveness associated with the task.
4. Quality: Measure and quantify the quality improvement.
5. Hazardousness, Tediousness: Measure and evaluate the hazards, the danger, and the degree of tediousness and unpleasantness associated with the task.
6. Economic analysis: Perform economic analysis in three different steps: in research, in development and feedback, and in the market.

However, difficulties appeared in effort to measure, quantify or evaluate some of the above aspects. Thus, a new system was developed which quantified these variables based on an industry system and fuzzy set linguistic variables.

#### **c) Stage Three**

In this stage some changes were made. First it was found that union plays a trivial role in our feasibility analysis and thus it was eliminated. Also a comprehensive detailed economic analysis was not possible at the present state of technology, since there was a lot of ambiguity associated with it. Thus, it was decided to employ a conceptual economic analysis based on the payback period evaluation.

Quality improvement, productivity, and degree of repetitiveness are all reflected in the economic analysis. In summary, the components of our analysis, as shown in Figure 12.3, are divided as follows:

1. State of Technology: To introduce those tasks that have potentials to be robotized at the present state of technology and give the necessary requirements to perform such task.
2. Hazardousness: Same as described in Stage Two.
3. Tediousness: Same as described in Stage Two.
4. Cost and Economic analysis: Conceptual analysis based on the payback period evaluation and by including quality, and productivity.

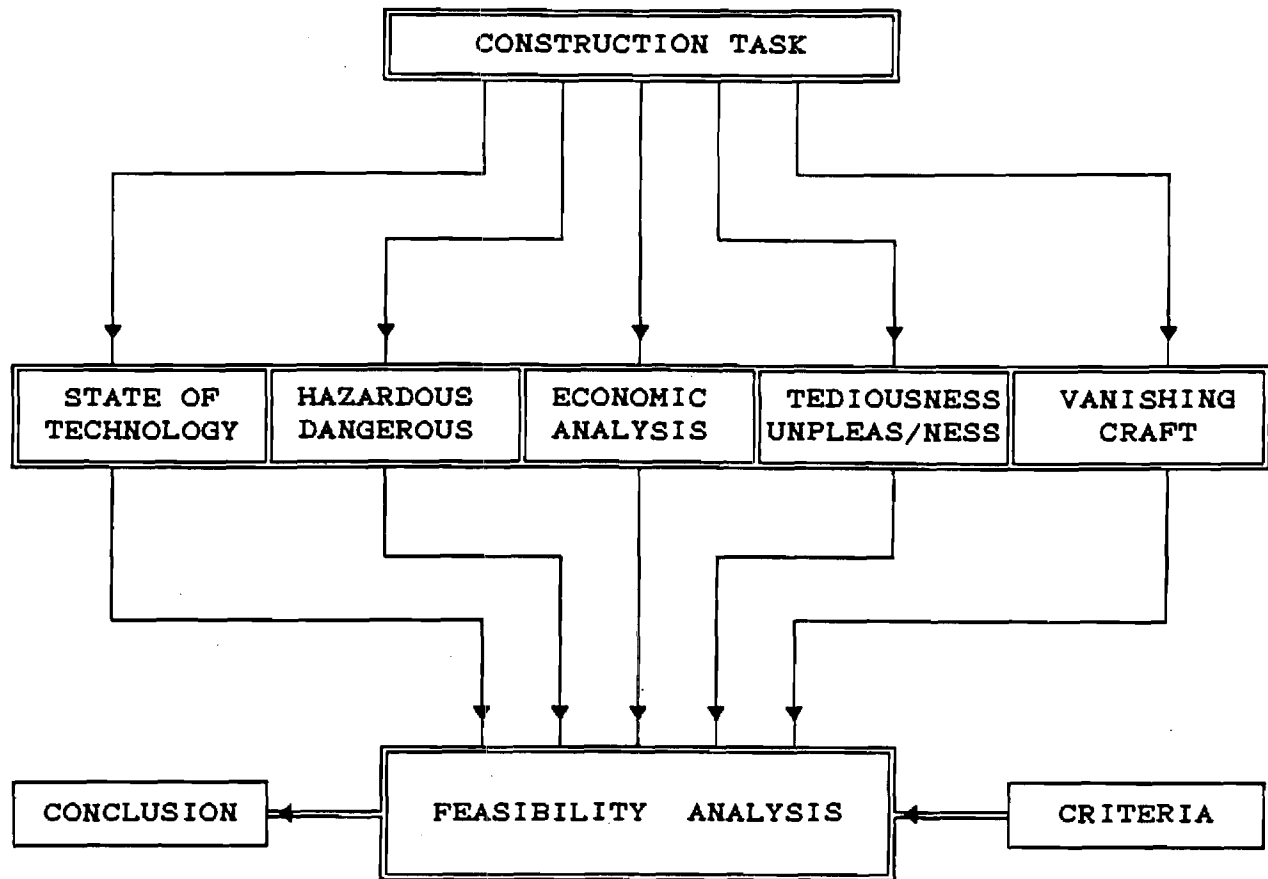


FIGURE 12.3 Components Of Feasibility Analysis (Final Stage)

5. Vanishing Crafts: Evaluated by the effect of craftsmen vanishing on the feasibility analysis of robotization in construction

### Cost Analysis

The cost analysis model is done based on fixed and variable costs as shown in the following equation.

$$(\text{Total Cost of Robot}) = a(\text{Number of Units Produced}) + b \quad (12.1)$$

in which  $a$  = variable cost; and  $b$  = fixed cost. If Equation 12.1 is divided by "Number of Units Produced", then Equation 12.2 can be shown as:

$$\frac{\text{Total Cost}}{\text{Number of Units}} = a + \frac{b}{\text{Number of Units}} \quad (12.2)$$

This equation can be shown graphically as Figure 12.4. Similar curves can be developed for conventional construction equipment, and fixed automation. These curves are presented in Figure 12.5. This figure shows the relation between unit cost and number of units produced. The intersection points show that operation should change from conventional equipment to robot or fixed automation. To make robots cost effective, the number of units produced must fall within a particular range.

Applying robotics to a particular construction operation will most likely involve a large initial capital investment. Capital investments are based on the evaluation of the spending requirements and the returns generated over the lifetime of the equipment.

Several construction projects involve a determined amount of repetitive operations but it does not mean that this operation should be immediately robotized. Basically, the decision is based on quantity parameters. Parameters that have been calculated based on economic analysis of production.

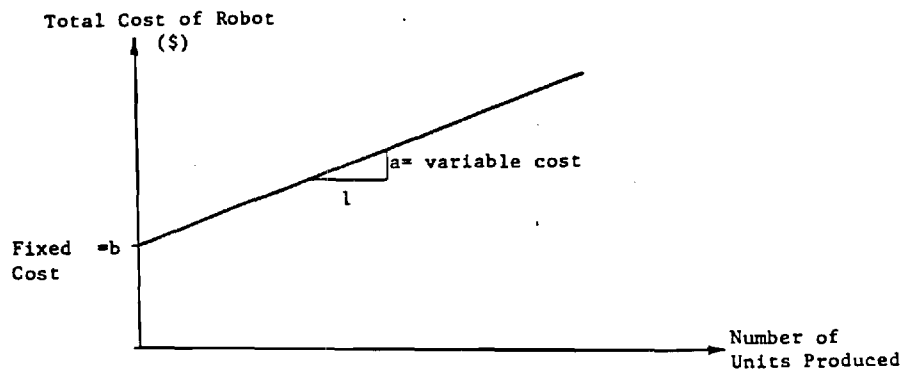


FIGURE 12.4 Total Cost Analysis

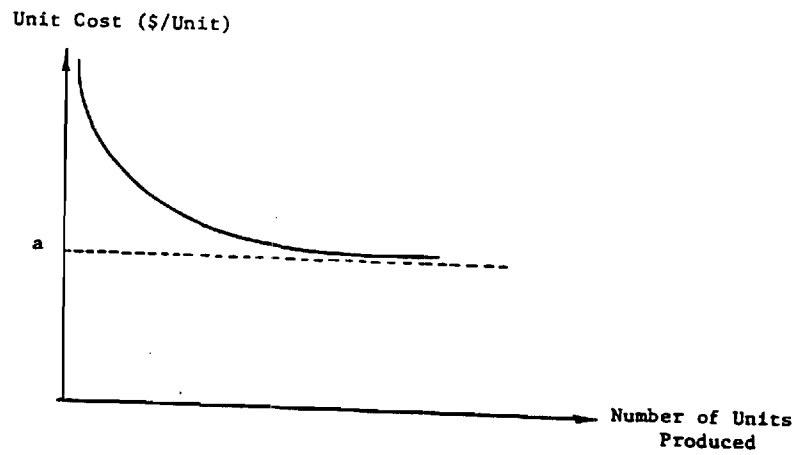


FIGURE 12.5 Unit Cost Analysis

Figure 12.6 shows the relation between unit cost and number of units produced, and shows if an operation should be utilized man power, conventional machines, robot, or fixed automation based on the different quantity parameters  $n_1$ ,  $n_2$ ,  $n_3$ , and  $n_4$ .

To determine whether a robot is economically feasible, costs and benefits should carefully be studied. There are basically two major economic analysis techniques for evaluating the desirability of a robot: 1) payback period analysis; and 2) cash flow analysis.

The payback period estimates the length of time (e.g., how many years) it will take to recover investment costs as shown in Eq. 12.3.

$$\text{Payback Period} = \frac{\text{Total Initial Capital Investment}}{\text{Annual Savings Resulting from the Robot}} \quad (12.3)$$

In general, a determination of the total investment required is necessary, then the effect of the investment on operation's expenses and profitability should be analyzed. Eq. 12.4 provides a simplified way to determine a payback period:

$$P = \frac{C}{L+D+I-M} \quad (12.4)$$

in which  $P$  = payback period in years;  $C$  = total initial capital investment required in robot and accessories,  $L$  = savings on annual labor costs due to the replacement of the robot;  $D$  = annual depreciation;  $I$  = annual savings resulting from increase in annual production and improved product quality, the value of  $I$  should be considered negative if there is a decrease in annual production; and  $M$  = annual robot maintenance costs. In general, the values of  $L$  and  $I$  can be estimated from Eqs. 12.5, and 12.6, as follow:

$$L = W - S \quad (12.5)$$

$$I = q(L+Z) \quad (12.6)$$

in which  $W$  = annual cost of workers before the implementation of robot;  $S$  = annual cost of staffing after the use of robot,  $q$  = speedup (or slowdown) factor due to the increase (or decrease) of annual production when a robot is used; and  $Z$  = annualized value of the robot, in general, it



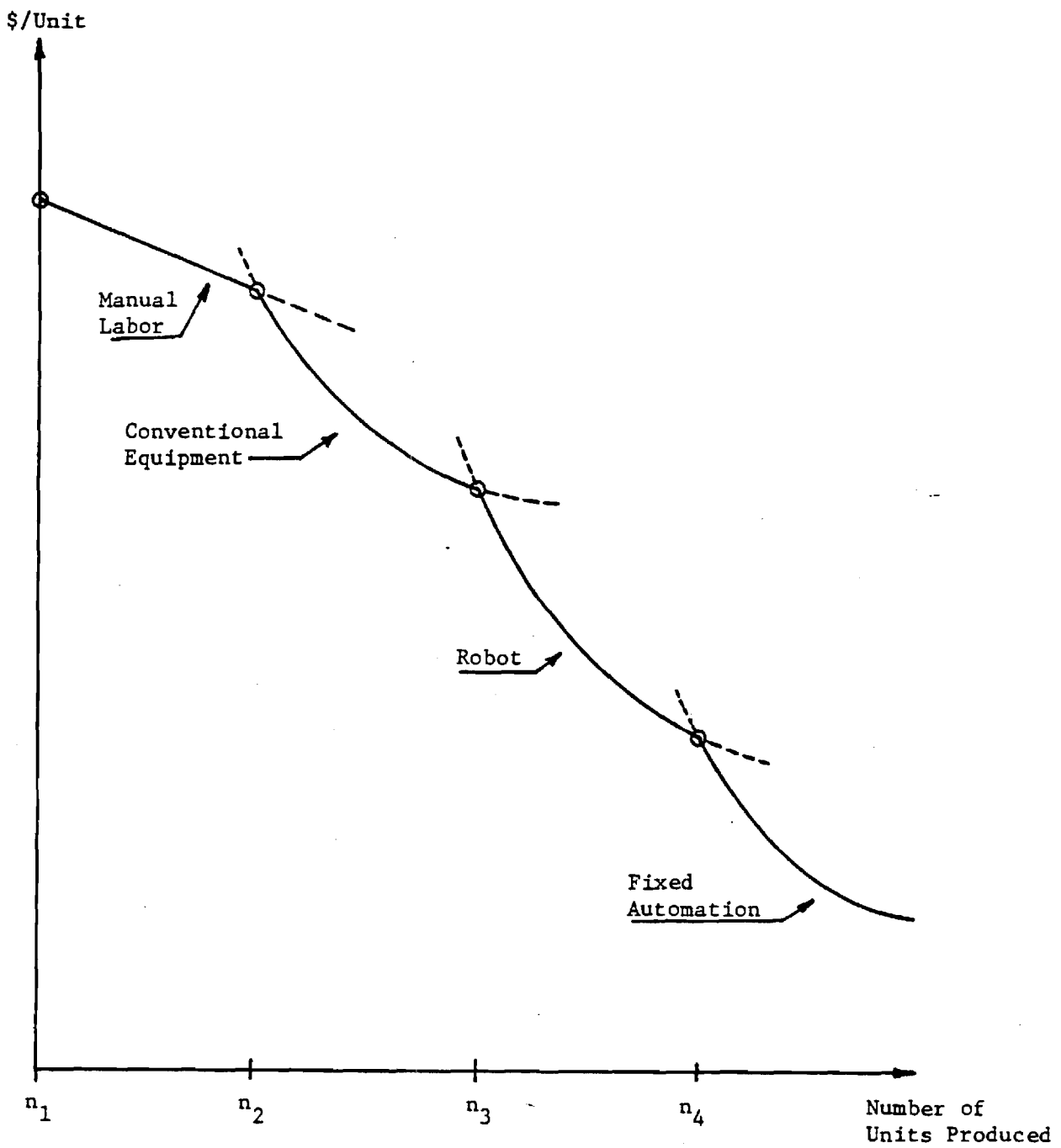


FIGURE 12.6 Evaluating Optimum Number Of Units

might be assumed as annual depreciation. Current robots have payback periods of 2-3 years when compared against direct labor.

Another method of economic analysis is the cash flow analysis. In this case, either annual rate of return (internal rate of return) on robot investment can be estimated, or the net present value of the investment can be calculated by applying a required or an appropriate rate of return for the robot. This method requires that an expected net cash flow be developed, and a discount rate must be assumed. Table 12.2 identifies the major cost and benefit items to be considered in the cash flow analysis.

### **A Prototype Development**

A microcomputer knowledge-based expert system shell program called INSIGHT 2+ was implemented for this analysis. The program starts by asking the user to weigh the four major components of our analysis (the technology component is always critical). The purpose is to assign a relative weight factor for each component.

The next step is for the program to know which construction task we are interest to robotize. If our task is not among those given in the list, then its robotization is not feasible at the present state of technology. If the task appears in this list then the program displays the robot requirements necessary for performance of this task. If available, the program also displays information about existing robots that can serve this task. The program also assigns a number between 25 and 100, rating the possibility of robotics technology to fulfill our task requirements.

Then the program continues with questions in hazardousness, tediousness, craftsmen vanishing, and economic analysis, assigning ranking numbers to each of them. These numbers will then be fed into the logic of the program to justify the degree of feasibility for robotizing the task under consideration.

Cash Flow	Items to be Considered
1) CASH OUT FLOWS	a) Total Robot Cost : Robot Accessories Options Installation  b) Maintenance Cost: Spare Parts Maintenance  c) Downtime Cost  d) Increase in Energy Cost
2) CASH IN FLOWS	a) Savings on Labor Costs  b) Productivity and Quality Improvement  c) Depreciation Saving Through Tax  d) Salvage Value

TABLE 12.2 Cost Analysis and Cash Flow

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**SECOND CONFERENCE ON  
ROBOTICS IN CONSTRUCTION**

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# Robotics Feasibility in the Construction Industry

By: Roozbeh Kangari

## I. INTRODUCTION

At the present time, robotics in construction industry is in the early stage of research. Before robots can practically be implemented in the industry, major problems such as: how construction processes can be automated; what are the sequential stages in construction automation; and what level of automation is feasible for a given construction operation should be investigated. Unlike the manufacturing industry, a construction site is a dynamic and random environment, therefore, a fully automated process requires a very intelligent control system, sophisticated sensors for feedback, an efficient material-handling system, and an advance mobility system. Under these conditions, it has become useful to explore at least those problems in the range of preliminary-steps for the robotics feasibility in the construction industry.

Robot is used extensively by the manufacturing industry. However, construction industry has unique characteristics which makes the robotization in most cases not a feasible alternative at the present time. It is not expected that robots enter the construction trades before the end of next decade. The construction site is a random environment requiring a robot of highly sophisticated intelligence combined with a large load range and need for mobility. It seems that in the early days of robotics application in construction industry, the awareness of construction site hazards to labors will provide the prime motivation to design and use a robot that would perform the tedious, repetitive, boring, dangerous and unpleasant construction jobs.

Robot technology is not new, but many industries as construction are only just beginning to realize the impact that full automation could have in their production. Today, construction robots are still on the stage of research, and there are only few practical construction robots developed in the U.S., Japan, and some other countries. However, among all these robots only one or two may be called real construction robot, and the rest are partially automated construction equipment.

Although today there is differences of opinion about exactly what a construction robot is, but in general may be defined as a fully automated mechanical device that can be programmed to perform construction tasks. In other words, robots are the machines which are controlled by computers.

A further essential question is the determination of an economical and practical level of automation for construction processes. There should be an optimum level of automation for each type of construction operation since excessive application of automation to a given process may not be economical. In certain cases, partial automation or robotization may even lead to an increase in the unit price. One approach to this question is to develop sequential stages in automation and perform a feasibility analysis for each stage.

#### SEQUENTIAL STAGES IN AUTOMATION:

To define an optimum level of automation for a given construction operation, the following five basic classifications as shown in Fig. 1 are developed:

- 1) Pure manual labor construction operation which involves no tools, e.g., material handling by hand, or packing.
- 2) Manual labor construction operation with tools, e.g., manual



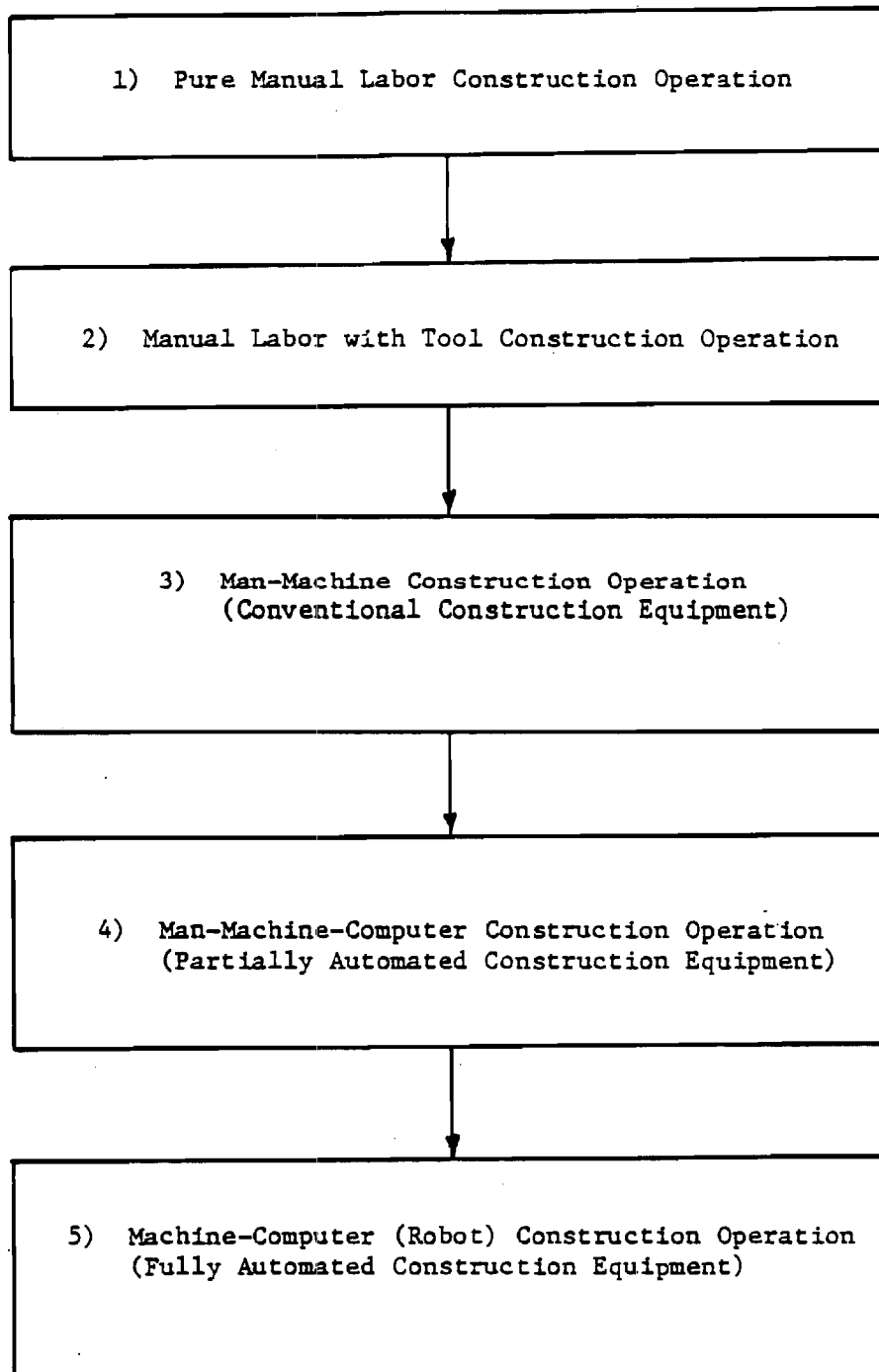


Fig. 1. - Sequential Stages in Construction Automation Process

excavation with a shovel.

- 3) Conventional construction equipment, or man-machine operation.  
These are the construction machines which are controlled by human, e.g., drilling rock by a conventional drill, or excavation by a conventional loader. Most of the construction equipment at the present time are under this classification. Fig. 2 represents a simple graphical model of this stage.
- 4) Partially automated construction equipment, or man-machine-computer operation. As shown in Fig. 3, this stage of automation improves the conventional construction equipment by adding a partially automated control system to the actuators, e.g., laser leveling grader, automatic gear shifting scrapers, hydraulic excavator with bucket tilt control, or remote control construction equipment for the construction work in dangerous places.
- 5) Fully automated construction equipment (robot), or machine-computer operation, e.g., SSR-2 spray robot for fireproof spraying on steel structures, developed by the Research Institute and Construction Machinery Division of Shimizue Construction Co. in Japan. In the U.S., the Civil Engineering and Construction Robotics Laboratory at Carnegie-Mellon University is heavily involved in research and development of the construction robots to perform tasks in environment that are unsafe for human. These robots require occasional human involvement as shown in Fig. 4.

How does a robot operate? Essentially the computer or robot is provided with information representing a model of the robot, with details of the environment, data relating to the tasks to be performed and with a number of planning algorithms. When in operation it receives at all times

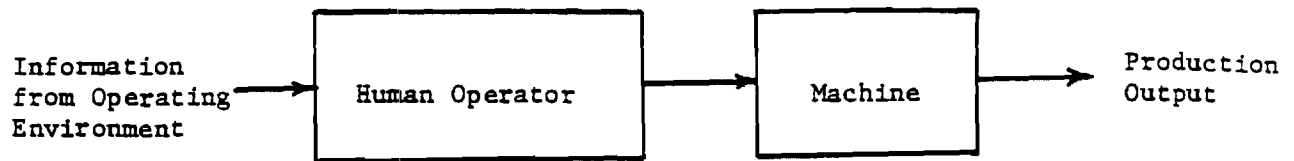


Fig. 2. - Conventional Construction Equipment

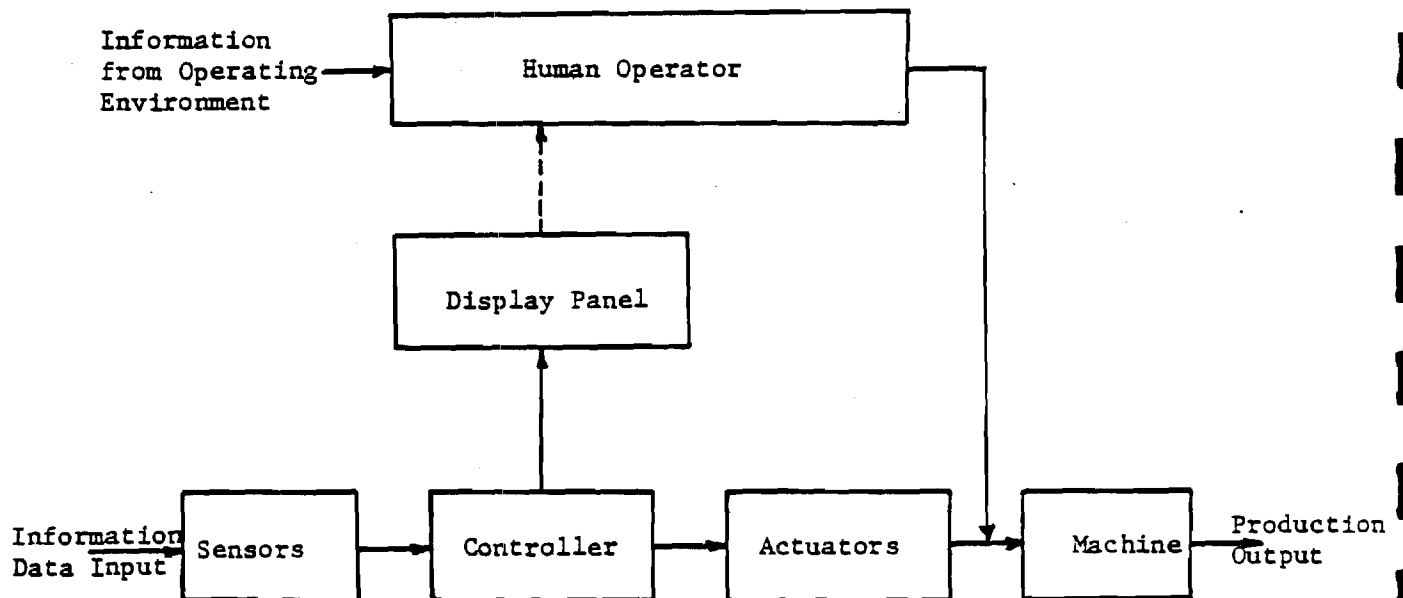


Fig. 3. - Partially Automated Construction Equipment

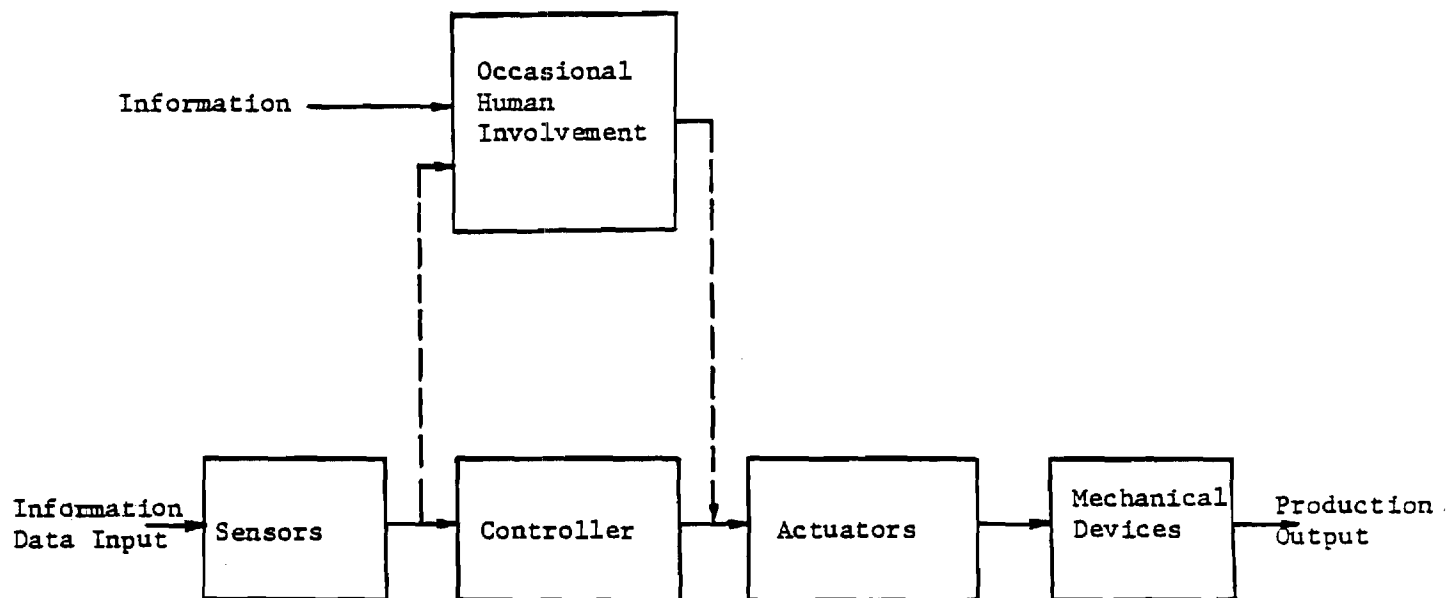


Fig. 4. - Fully Automated Construction Equipment (Robot)

information concerning the robot with internally sensed information, and the environment with externally sensed information. By using this information in conjunction with planning algorithms, which can refer back to past experience, the computer develops control over the robot, causing it to move towards the correct execution of the task assigned to it.

The main difference between a construction robot and a conventional construction equipment is that the robot is able to react with its environment without a human intervention. However, the publicity surrounding the introduction of robots into construction field exaggerates the true state of the theoretical and practical knowledge of robotics. The technical challenge is considerable because, at present, the characteristics of robot are far from attaining the performance required in an unstructured and dynamic construction field.

Large construction companies with an interest on equipment automation have not given a great deal of attention to research in robotics. There are only a few international contractors who have introduced robotics into their field, however, these robots are not capable of detecting the complex information directed to them from the environment.

If the number of repetitive operations are very large and the output product is fixed, then it might be economical to implement a fixed automation plant. For example, if a prefabricated plant is planning to build a large (infinite) number of fixed construction products (e.g., prestressed concrete beams) which does not require any change in size or type of material, then a fixed automation may reach a lower unit price than a flexible automated plant. This is due to the large volume of production and a lower variable cost.

Considering these sequential stages, the objective of this paper is to describe the feasibility of the last stage (robotization) in relation with the other stages. In other words, what construction operations should be robotized.

## II. FEASIBILITY ANALYSIS

A modelling procedure is needed to evaluate the feasibility of developing robotics and justifying the implementation of robotics for certain construction operations. Two feasibility models using seven basic variables are proposed. The ultimate output of the models indicate whether the robotization is appropriate for a particular construction operation or not. In reality, robotics feasibility and justification is interdisciplinary since it involves the input of several professional groups, therefore, this paper can only provide a guide for evaluation and discuss general considerations.

The goal is to develop generalized mathematical models for evaluating the suitability of robotics applications in the construction industry. That is, what construction operations can be robotized? To answer this question, a robotization index,  $I$ , must be obtained such that a given value or range of values indicates whether robotics is feasible for a particular construction operation at a given point in time. A linear scale of the index can be utilized as shown in Fig. 5.

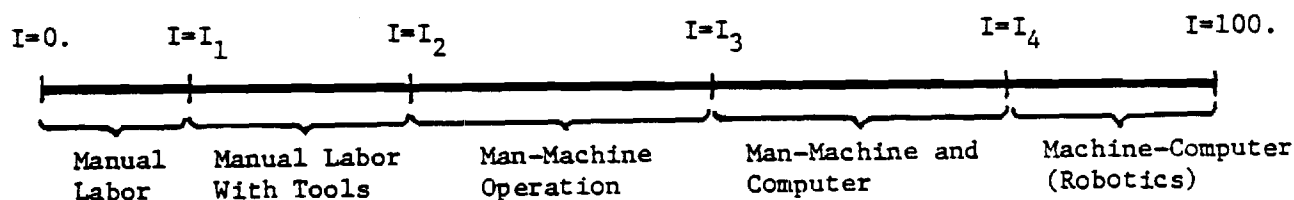


Fig. 5. - Linear Scale of Construction Operation Index

To determine this index, the following seven major variables affecting on the feasibility of the robotics are considered:

- 1) Cost Effectiveness and Economical Analysis
- 2) Level of Hazardous
- 3) Productivity
- 4) Quality Improvement
- 5) Standardization of Design and Level of Repetitiveness
- 6) Union Resistance
- 7) Technologically Feasible

Any construction operation, if desired to be robotized, should satisfy a certain level of these variables. Since each construction operation is unique in nature, therefore, each operation will have different weight factors to the above variables depending on their level of importance in the operation. For example, in a welding operation inside a nuclear power plant with a high level of radiation, variables 2 and 7 will have higher weights than variable 5.

These variables must be analyzed in order to determine whether a particular operation should or should not be robotized. Next, these variables are defined and discussed.

#### Cost Effectiveness and Economic Analysis:

Applying robotics to a particular construction operation will most likely involve a large initial capital investment. Capital investments are based on the evaluation of the spending requirements and the returns



generated over the lifetime of the equipment. Sometimes a particular construction operation is technologically feasible but not financially.

To determine whether a robot is economically feasible, costs and benefits should carefully be studied. There are basically two major economic analysis techniques for evaluating the desirability of a robot:

1) payback period analysis; and 2) cash flow analysis.

The payback period estimates the length of time (e.g., how many years) it will take to recover investment costs as shown in Eq. 1.

$$\text{Payback Period} = \frac{\text{Total Initial Capital Investment}}{\text{Annual Savings Resulting from the Robot}} \quad (1)$$

In general, a determination of the total investment required is necessary, then the effect of the investment on operation's expenses and profitability should be analyzed. Eq. 2 provides a simplified way to determine a payback period:

$$P = \frac{C}{L+D+I-M} \quad (2)$$

in which P = payback period in years; C = total initial capital investment required in robot and accessories, L = savings on annual labor costs due to the replacement of the robot; D = annual depreciation; I = annual savings resulting from increase in annual production and improved product quality, the value of I should be considered negative if there is a decrease in annual production; and M = annual robot maintenance costs. In general, the values of L and I can be estimated from Eqs. 3 and 4, as follow:

$$L = W - S \quad (3)$$

$$I = q(L+Z) \quad (4)$$

in which W = annual cost of workers before the implementation of robot; S = annual cost of staffing after the use of robot, q = speedup (or slowdown)

factor due to the increase (or decrease) of annual production when a robot is used; and  $Z$  = annualized value of the robot, in general, it might be assumed as annual depreciation. Current robots have payback periods of 2-3 years when compared against direct labor.

Another method of economic analysis is the cash flow analysis. In this case, either annual rate of return (internal rate of return) on robot investment can be estimated, or the net present value of the investment can be calculated by applying a required or an appropriate rate of return for the robot. This method requires that an expected net cash flow be developed, and a discount rate must be assumed. Table 1 identifies the major cost and benefit items to be considered in the cash flow analysis.

#### Level of Hazardous

Hazardous construction operations are very suitable for the robotization. The distinction between unsafe operations and hazardous operations should be made. Unsafe operations are assumed those in which there is a high occurrence of worker accidents. Accidents are considered to be the fault of the worker, either through carelessness or by the misuse of equipment. Hazardous operations are assumed those operations which expose the worker to an unhealthy environment (e.g., dust, radiation, heat, etc.). The worker is not considered responsible for the conditions but due to the nature of the operation, unhealthy human exposure is required. Historical data generally indicates the frequency of job related accidents, while standards relating to hazardous operations are provided by OSHA.

Some of the construction operations are hazardous, therefore, governmental and private agencies have dedicated special attention to this kind of operations. Several studies have conducted in which permissible

TABLE 1. - Economic Analysis of a Robot

Cash Flow	Items to be Considered
1) CASH OUT FLOWS	a) Total Robot Cost : Robot Accessories Options Installation  b) Maintenance Cost: Spare Parts Maintenance  c) Downtime Cost  d) Increase in Energy Cost
2) CASH IN FLOWS	a) Savings on Labor Costs  b) Productivity and Quality Improvement  c) Depreciation Saving Through Tax  d) Salvage Value

exposure limits for a variety of noxious elements commonly found in construction operations have been set. In determining if a particular operation is hazardous, the following elements should be analyzed.:

- 1) Concentration of Dust.      Asbestos      Zinc  
   Beryllium      Cement  
   Uranium      Fibrous Glass
- 2) Temperature Levels
- 3) Air and Water Pressures
- 4) Noise
- 5) Radiation

Some of the current permissible exposure levels that have been set by different governmental and private agencies are:

Dust - Any job site in which atmosphere contains dust particles smaller than 5  $\mu$ m in aerodynamic diameter are considered hazardous for the human lungs.

Toxic Dust, Gases, and Fumes.

- Job sites in which Chemical particles and substances are found in a level superior to .15 mg/m<sup>3</sup> of air.

Noise - Any job site in which sound levels exceeds 115 dBA. is considered hazardous for the human health.

Radiation.

- The permissible exposure levels should be  $\leq$  3 REM. per calendar quarter or  $\leq$  5 REM. per year.

Unsafe operations such as: sloped excavations, tunnel excavations; and scaffolding operations can also be analyzed in similar way.

## Productivity

Productivity levels in a particular operation are indicators of the effectiveness of the different resources involved in the operation.

In order to determine if a particular operation is suitable for robotization from the point of view of productivity, it is necessary to set a desired or expected productivity level. After having conducted a detailed and precise study of the productivity variation according to the type of machine being utilized and according to the expected robot productivity variation, the decision-maker should be in the position to decide if the operation is suitable for robotization or not.

Generally, productivity of an operation is measured by dividing the total number of units produced by the total amount of resources utilized in a determined period of time.

Productivity can simply be defined as the ratio of output to input, typically given as units produced per man-hours required. A comparison between productivities of the current system and the proposed robotic system should be made. If historical data on productivity is not available then a study to determine these values must be made. Cyclone modelling of the operation's tasks and sub-tasks for both systems may be used to determine the value of productivity. Several assumptions may be needed to model the robotic system, especially if it is a new or unique application. The most desirable results would indicate that the robotic system provides greater productivity in the comparison.

If a construction operation is automated or robotized, it is expected to have a sharp increase in the productivity. The increased productivity, supposedly, gradually absorbs the cost incurred in the robot or automated equipment implementation. Obviously, productivity is not the only factor

that pays for the robot. In some situations, the productivity achieved by a robotized operation remains the same, but substantial savings are expected to occur in other cost categories such as labor, overhead, etc., or even cost savings achieved by a better quality of the work.

A robot might have another uses in other projects. Therefore, the analysis must consider these possibilities, just to study whether or not the robot cost is commensurated by the better productivity achieved.

One must remember that certain construction operations involve a lot of risk. In this situation, the productivity plays a secondary role, because the main objective is to avoid detrimental and hazardous conditions. For these reasons, the project planner must weigh every factor accordingly to the desired goals.

#### Quality Improvement

One major reason for the implementation of robot is to produce a better quality compared to traditional systems. The results of quality analysis of the SSR-2 spray robot for fireproof cover work shows that the dispersion of the sprayed thickness decreased. Quality of a construction product can be measured by a numerical model which considers such characteristics as strength, dimension, color, and etc. Only the relevant characteristics of an operation product should be considered. There is a direct correlation between cost and the level of quality improved.

#### Standardization of Design and Level of Repetitiveness

The cyclic and repetitive operations are the most suitable operations to be robotized or automated. A repetitive routine operation is a

desirable operation characteristic for the robotization. A construction operation should be broken down into individual processes, tasks, and sub-tasks. The amount and type of repetition in each of these work divisions should be analyzed. The decision-maker determines the number of cyclic motions required in the production of one unit.

Standardization of design also involves repetition but on a larger scale. Here, repetition is studied on the project or activity level. Basically, this parameter evaluates the number of production units required for successful robot implementation. Justification depends upon whether the number of production units fall within an optimum range. If not, perhaps some other man/machine system is more appropriate.

There are several means by which the number of production unit in a project may be modified to fall within the optimum range for robotization. In the project planning phases it is advantageous to orient various building components (i.e. steel framing, doors, windows, rooms, etc.) in a regular and predictable manner increasing the feasibility of robotization by increasing the quantity of repetitious work cycles. Standard dimensions, regular geometric shapes and standard size fixtures would simplify implementation. Simplifying the construction design would in turn simplify the robot's job, reduce the necessary 'learning period' (teaching and reprogramming) and thereby increase robot effectiveness.

Standard design and repetitive operation are two factors that are required for robotization or automation of any construction operation.

Several construction projects involve a determined amount of repetitive operations but it does not mean that this operation should be immediately robotized. Basically, the decision is based on quantity

parameters. Parameters that have been calculated based on economic analysis of production.

Fig. 6 shows the relation between unit cost and number of units produced, and shows if an operation should be utilized man power, conventional machines, robot, or fixed automation based on the different quantity parameters  $n_1$ ,  $n_2$ ,  $n_3$ , and  $n_4$ .

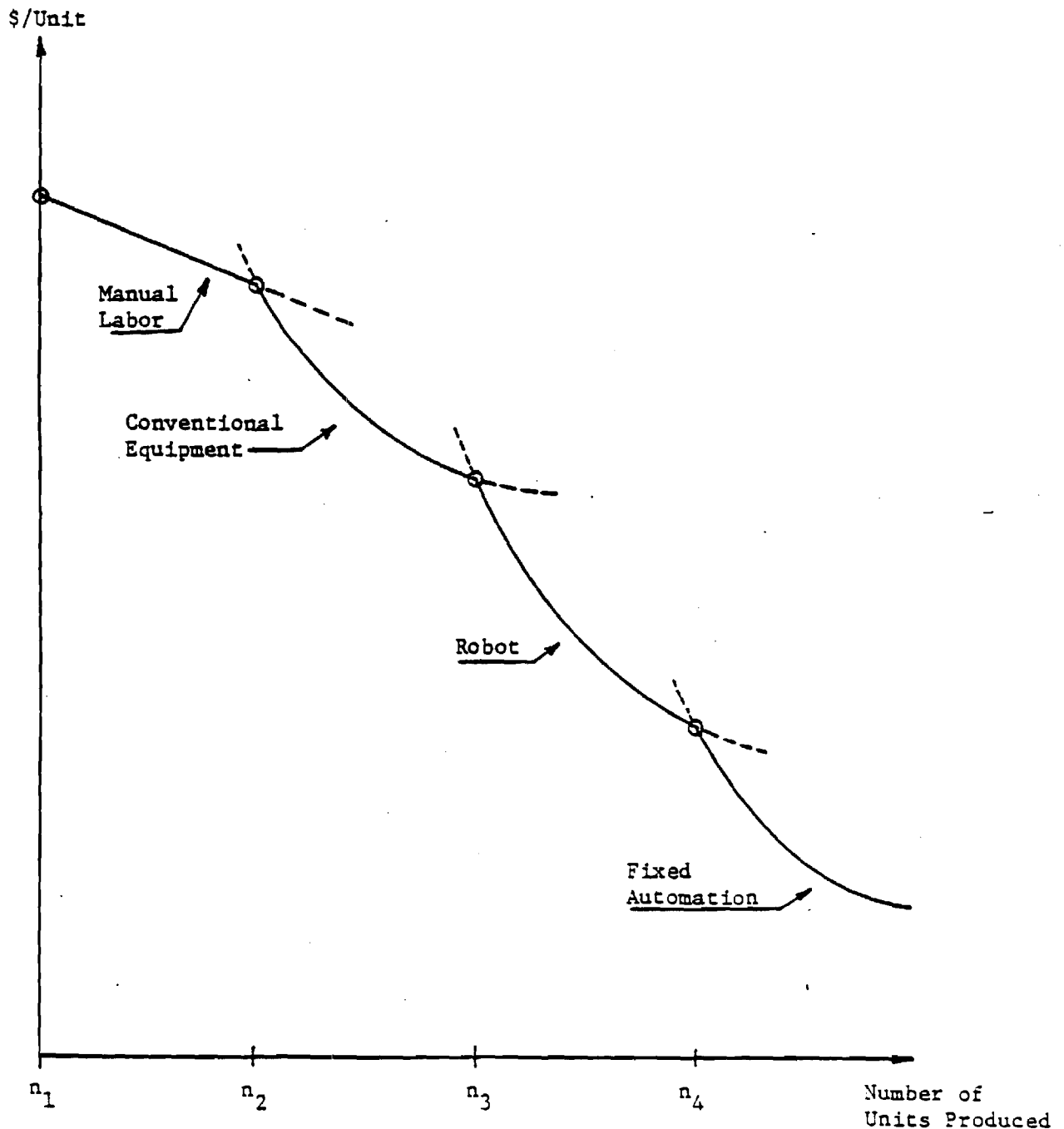


Fig. 6. - Economic Stages of Automation vs. Level of Repetitiveness



Because construction robot applications are in the first generation of development and the construction products are unique items, the standardization of design provides for an environment conducive to the favorable application of robots. Standardization can mean the uniform use of a particular design throughout the project or a series of uniform activities being recognized as appropriate for robotization. Specifically, the structural design should be simple and repetitive using standard dimensions. Thus, the standardization of design is highly dependent upon the future acceptance of limited design individuality in construction projects and the future development of robots to handle the various requirements of the construction site.

Since some activities may be repetitive but not standard, e.g., a unique design which is being used a multitude of times on a particular construction project. Repetitive activities will involve the cyclic movement of or sharing of resources. A procedure to determine the repetitive operation is to develop a number of units constructed versus cost per unit curve. A curve developed for the construction operation under study would yield a range such that  $n_3 < N < n_4$  would indicate robotization.

#### Union Resistance:

Labor unions currently have few standard policies concerning the automation or robotization of construction operations, therefore, the reaction from organized labor can only be estimated. Unions have traditionally viewed automation as providing improvements to working conditions and in most cases respond in a positive manner.

Union resistance is considered to be somewhat dependent upon the following:

- number of workers being displaced
- union strength in the area
- policies of management (advance notice to union officials, placement programs for displaced workers, etc.)

This parameter is more difficult to model because no definite measurement scale of union resistance exists.

Generally, unions resistance vary depending upon the kind of operation under consideration. If the robotization of a particular operation will represent the possibility of a massive labor's displacement, unions resistance could be so drastic that it could determine the success of the whole operation.

In order to minimize unions resistance, the decision-maker should be aware of the social implications of introducing new technology in the operation. Obviously, solutions to the problem could be possible, such as relocation of displaced workers within the industry or in other industries.

To reduce the union resistance, the following major factors must be considered by the contractors:

1. minimum social disruption should be generated
2. job safety and worker satisfaction should be given large consideration
3. the overall quality of life for workers should be enhanced.

An interview was conducted with the Business Manager of the Local 438 of the Laborers International Union of North America, located in Atlanta, Georgia, which is affiliated with the AFL-CIO. The objective was to ascertain the construction laborer's union's understanding of robotization

in the construction industry and the policy with regards to the robotization. The following questions (Q), and responses (R) were resulted from the interview:

Q-1 What is your idea of a robot?

R-1 A machine that accomplishes a task in a methodical and precise way. Not the science fiction version of humanoid-like machines in the movie Star Wars

Q-2 Do you see a place for robotics in the construction industry?

R-2 Yes, such as in painting applications, but we will still need human directions and involvement in site safety considerations.

Q-3 Are you familiar with the progress made in other countries such as Japan towards robotization of the construction industry?

R-3 I have heard bits and pieces about foreign robotics development but have no actual hands-on experience with foreign robot advancement in construction.

Q-4 Does the union have any input with regard to non-union jobs?

R-4 None whatsoever, and union influence is weak in Atlanta and is decreasing throughout the country.

Q-5 Does the union have a policy with regard to robots in construction? If not, is there any policy on automated equipment?

R-5 There is no current policy on robots with regards to construction. The policy with regards to any labor saving device is not to hinder any increase in productivity. However, any unique items are always negotiable points in contracts between the union and the construction contractor.

Q-6 Would the union object to placing robots in hazardous and/or harmful construction tasks?

- R-6 No, but it would be a negotiable item requiring assurances that the task be accomplished properly. I don't believe any construction job can be handled without human assistance. (This goes beyond supervision into actual task accomplishment.)
- Q-7 Is the current and future work environment in construction large enough to absorb a small percentage of workers who could be displaced by robots? If so, what percent would the union feel comfortable with?
- R-7 Take two of the same construction jobs over the last 30 years. A job using 150 bricklayers in 1950 would use 40 or so today because of improved construction techniques, materials, etc. There is no place to absorb workers displaced by robots. At this time, no percentage of displacement is a comfortable prospect.
- Q-8 If robots become a reality in the construction field, what in your opinion will be the most significant changes brought about in the workplace? To the individual worker?
- R-8 As many workers would be needed to direct or maintain the robots as are now needed to accomplish the work. Look at computers, which equate to robots in the sense of mechanizing human work tasks. They have created as many jobs as they have eliminated. (It was pointed out that the new jobs created were different and required a retraining process.)
- Q-9 If robots become feasible, would the economics of dollar savings be enough justification to displace workers? If not, what is the union's flexibility on this issue?
- R-9 The union has never stood in the way of progress. The papers

have given the unions bad press. In the last 30 years the displacement of workers has continually increased, and the union has accepted this as part of progress. The union has never struck against improvements.

Q-10 What stipulations would the union demand so that the least amount of disruption would affect the worker displaced by robotization?

R-10 Retraining the displaced workers so that they could maintain their self-respect and lead productive lives. This is the basic concept we would negotiate for.

Q-11 Do you believe that a future situation can exist where humans and robots work in the same environment without conflict?

R-11 Yes, robots can be utilized in construction working side-by-side with humans. It is happening now in automobile factories.

Q-12 Since the introduction of automation did not cause a mass unemployment crisis, do you see a parallel occurrence with the introduction of robots?

R-12 During my lifetime, there have been many revolutionary changes and mass unemployment did not result unless a depression was occurring. Robots, automation, whatever will not cause mass unemployment as long as people are retrained.

Q-13 Do you foresee a larger impact on minorities such as women and blacks from the robotization of the construction site?

R-13 No, not in union represented work. The union is an equalizer. Job assignments are handled fairly on a first-come-first-serve basis.

Q-14 An extreme reaction to robotics could be construction site sabotage. Could you foresee such incidents even if the unions

deplore such tactics?

R-14 People will do most anything if pushed to the extreme, but the union would not condone such activities. If mass unemployment resulted, repercussions would probably occur here in Atlanta.

Q-15 How would a program for the retraining of displaced workers be set up?

R-15 We have a training school in Atlanta which is contractually funded through negotiated dollar amounts set aside per worker hour. Any retraining program would use this existing system.

Q-16 Would the union consider requesting government intervention to either delay or prohibit robotization in construction?

R-16 We belong to the AFL-CIO and they are our political arm. They have a lobby like everybody else. So, we would lobby if it became important to our union members.

Q-17 What about the workers who are not displaced? Will they need some kind of training to function better in the new robotic work environment?

R-17 Possibly, and if so we would use the existing training system mentioned earlier.

Q-18 What job security techniques would the union utilize to assure minimum worker disruption?

R-18 We would explore every avenue available such as more vacation time, same pay for less time worked, etc. Of course, this would depend on the negotiation process.

Q-19 Would the knowledge that foreign competition through the utilization of robots on construction projects was placing American companies in an unfavorable position cause the union to accept

robotization in the USA more readily?

R-19 We would prefer that anything be American made and better yet, union made. Therefore, we would work with the contractor to stay competitive.

Q-20 Would the union be interested in the results of the research currently being done at Georgia Tech and help in drafting a policy guideline with regards to robotic applications in construction?

R-20 At this time no policy exists nor is one being developed, but we would certainly be open to any help on robots when the issue becomes pertinent to us.

It should be mentioned that the above interview is not an appropriate sample size to draw a general conclusion with high degree of confidence, similar questions must be asked from a broad range of union representatives at all levels of authority and all regions of the United States.

#### Technologically Feasible

In spite of the technological advances achieved in the last few years, technology does not always provide the necessary elements to develop machines for certain kind of industrial operations. For this reason, it is important that this factor be analyzed in the first stages of the study in order to determine if technology provides the tools to develop the appropriate machine for the operation in question. If the study reveals that development of a robot is not technologically feasible, further study of the other factors are not necessary, since the whole operation cannot be achieved.

The various aspects to be analyzed in this area are:

- 1) Type of Mobility of Robot
  - a. Wheels, tracks or walking devices
  - b. Carriage system (traveling and standing frames)
- 2) Robot's Manipulators
- 3) Control Systems
- 4) Methods of the Construction Material Supply
- 5) Weight of Robot (within design load)
- 6) Size of Robot
- 7) Robot's Safety Functions (human life and limb protection)

It is expected that mobile robots will find increased popularity in construction industry. A fixed robot has a limited sphere of operation and is not appropriate for the construction sites.

A construction wheeled vehicle robot, such as a motor car, with firmly inflated tires represents an ideal system with minimum eneregy to operate on smooth surfaces which have sufficient friction to the wheels to propel and steer the robot without slipping. Wheeled systems can only operate over relatively smooth surfaces. The track systems are the known alternatives to wheels for rough ground mobility.



### III. FEASIBILITY MODELS

Two basic feasibility models are presented for justifying the implementation of robotics in certain construction operations: 1) a simplified management decision model; and 2) utility decision model. The first step in the formation of the models is to identify the relevant variables. The second step is to develop a criteria for estimating a management decision index.

#### 1) Simplified Management Decision Model:

This model allows the management to make a quick decision about the automation or robotization of a particular construction operation. The seven major variables discussed previously are considered as major management decision variables as shown in Table 2. Different weight factors should be assigned by the management to each variable. These weight factors indicate the level of importance of the variables, and they may vary one operation to the other. Columns 3 and 4 show the actual and acceptable standard levels of the variables. For example, as shown in Table 2, for a given construction operation the level of dust is measured as 3  $\mu\text{m}$ , however based on the N.S.C. safety and health standards, the acceptable level of dust is 5  $\mu\text{m}$ . Since the measured particles of dust are smaller than the standard size, therefore, this construction operation is unsafe, and it is appropriate for the robotization.

The index for other variables are evaluated as described in previous sections. Some indices may not be possible to evaluate, such as union resistance, in this case, a 'Yes' or 'No' answer is sufficient. Column 5 shows the necessary relation between columns 3 and 4 in order to robotize. If the relation on column 5 holds, then a 'Yes' answer with the given

TABLE 2. - A Simplified Management Decision Model

Major Decision Variables	Level of Importance (Weight Factor)	Measured Index of the Variables	Standard Index of the Variables	Necessary Relation for the Robotization	Yes - Robotize if (5) holds	No - Robotize if (5) does not hold
(1)	(2)	(3)	(4)	(5)	(6)	(7)
1) Economic Analysis (Payback Period)	$w_1 = 30$ points	$i_1 = 2$ years	$I_1 = 2.5$ years	$I_1 > i_1$	Yes = 30 points	—
2) Level of Hazardous Dust Level Radiation Level etc.	$w_2 = 25$ points	$i_2 = 3 \mu\text{m}$	$I_2 = 5 \mu\text{m}$	$I_2 > i_2$	Yes = 25 points	—
3) Productivity	$w_3 = 10$ points	$i_3 = 200$ units/hr	$I_3 = 150$ units/hr	$I_3 < i_3$	Yes = 10 points	—
4) Quality Improvement	$w_4 = 10$ points	—	—	$I_4 < i_4$	Yes = 10 points	—
5) Level of Repetitiveness	$w_5 = 5$ points	$i_5 = 865\text{K}$ units	$I_5 = 500\text{K}$ units	$I_5 < i_5$	Yes = 5 points	—
6) Union Resistance	$w_6 = 5$ points	—	—	$I_6 < i_6$	—	No = 5 points
7) Technologically Feasible	$w_7 = 15$ points	—	—	$I_7 > i_7$	Yes = 15 points	—
TOTAL	100 points				Yes = 95 points	No = 5 points

weight factor should be entered in column 6, otherwise, a 'No' answer with the same weight factor will be assigned to the column 7. Total of columns 6, and 7 are shown on the last line. It is the management decision to find the cut-off points of the 'Yes' answers. It is suggested that those operations with 75 points or more 'Yes' answers should be carefully analyzed for the robotization.

## 2) Detailed Feasibility Analysis by Utility Model:

The management model described is a simple 'Yes' or 'No' analysis which can be used for the preliminary feasibility study of the robotization. A utility model is developed in this section to allow the contractors a detailed study of the operation.

This model assumes that it is technologically feasible to build a robot, and those operations which are not technologically feasible cannot be implemented, therefore, they do not apply to the modeling process. To avoid the double counting of the variables, those variables with high correlation will be combined. Such as productivity and payback period will be assumed as one variable due to their high correlation.

This model implements the utility theory to establish a utility function for each of the variables, then these utility functions are combined to estimate a single index of robotization. The following variables with low correlations have been considered in this model: a) payback period, b) level of hazardous, c) quality, d) level of repetitiveness, e) union resistance.

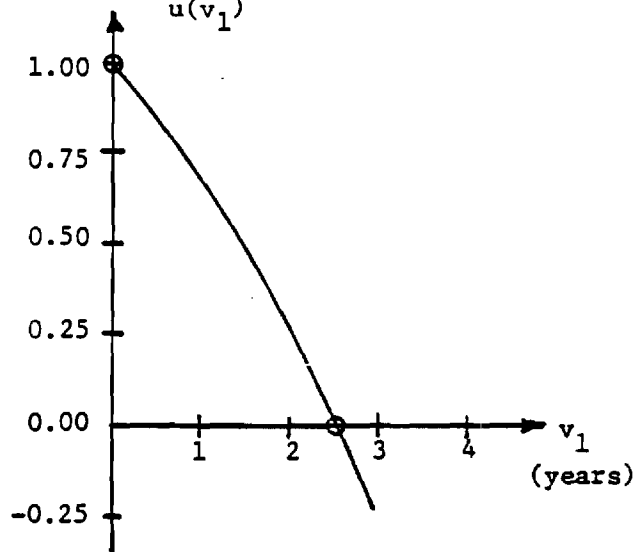
The next step in the modeling process is to assign acceptable upper and lower limits to the possible range of values in each variable. Both desirable and undesirable magnitudes should be included in the range. As

shown in Fig. 7, these values are plotted along a horizontal axis, and the utility scale is the vertical axis. Two points on the utility scale are defined: 1.00 is assigned to the most preferred value, and zero is assigned to the point lying directly between the desirable values and undesirable values, a neutral point. A utility function can be developed between the two points on the scale.

As shown in Fig. 7a, a payback period of zero year is assumed to have the highest utility, and an accepted period of 2.5 years by the industry as the indifference point. In Fig. 7b, a dust particle size of  $5\text{ }\mu\text{m}$  is assumed as indifference point, in other words, if the level of dust particles are less than  $5\text{ }\mu\text{m}$ , then the operation is suitable for the robotization, therefore, it has a positive utility (satisfaction). Fig. 7c shows two levels of quality  $a_1$  and  $a_2$  with zero and one utility value. These values must be estimated by the management. If the quality of the work performed by robot has a value less than  $a_1$ , then the implementation of robot based on this variable is not desirable. Fig. 7d is developed based on Fig. 6. If the level of repetitiveness is between  $n_3$  and  $n_4$ , then the robots should be used. Level of  $n_4$  is an optimum repetition when the robotization is compared with the fixed automation. Fig. 7e divides the level of the union resistance into three levels: low, medium, and high. An average medium level is considered as zero utility. The assigned values should be adjusted by the decision maker under different conditions.

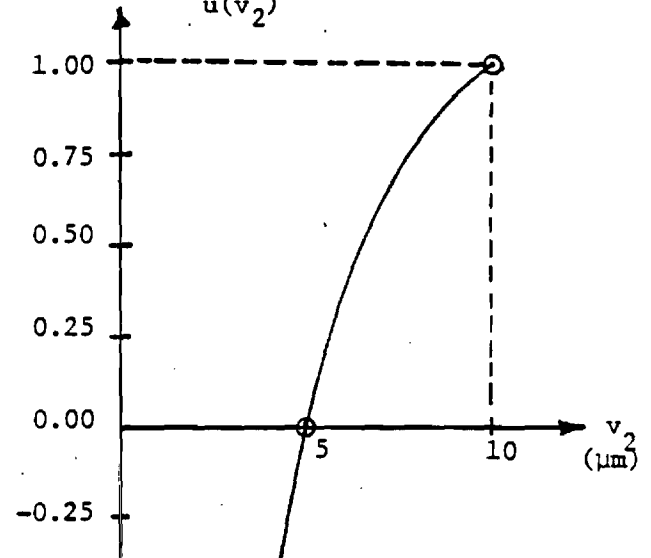
To consider the impact of different variables and their individual contribution to the overall index, each of the measurement scales must be converted to one common scale. A set of scaling factors (weight factors) is used in the conversion. Each variable receives a scaling factor, the magnitude of which is based on the estimated importance of the variable to

Utility of First Variable  
 $u(v_1)$



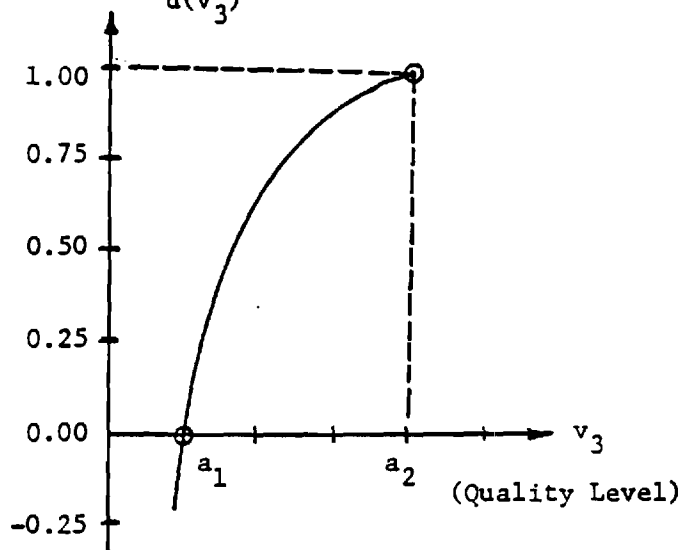
a) Payback Period vs. Utility

Utility of Second Variable  
 $u(v_2)$



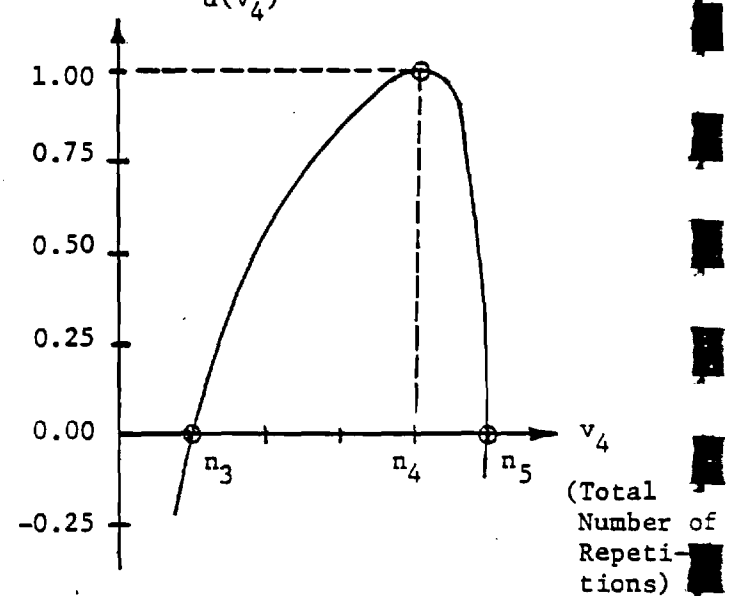
b) Size of Dust Particles vs. Utility

Utility of Third Variable  
 $u(v_3)$

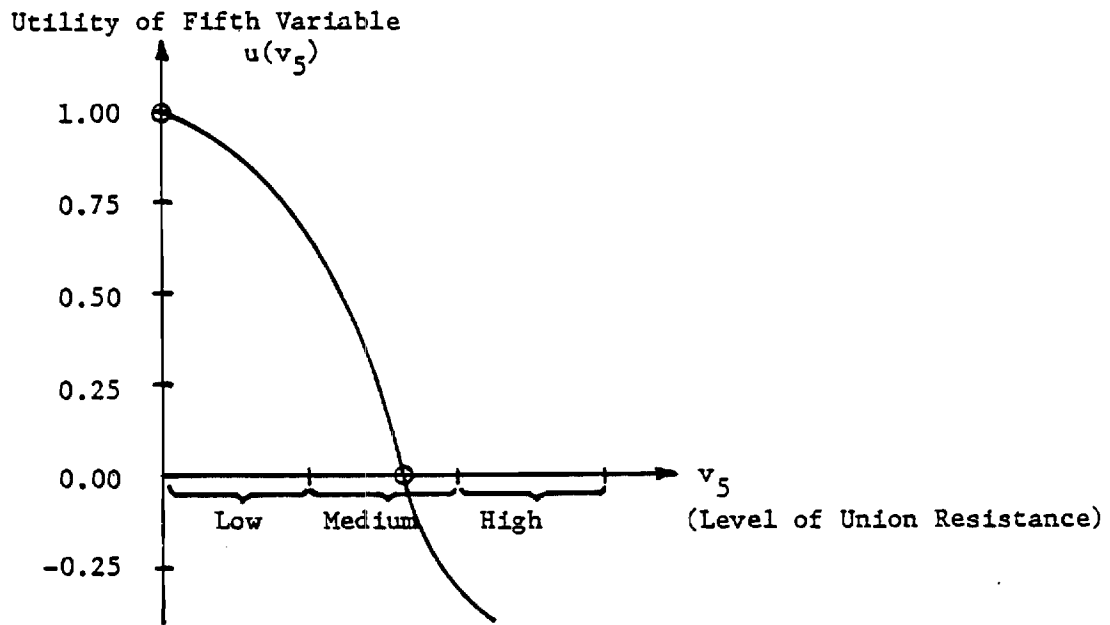


c) Quality vs. Utility

Utility of Fourth Variable  
 $u(v_4)$



d) Level of Repetitiveness vs. Utility



e) Union Resistance Level vs. Utility

Fig. 7.- Utility Function of Each Variable

the index. Each utility is multiplied by its scaling factor as shown in Eq. 5. The products are then summed to yield a total relative index for the operation. The alternatives with the highest global utility (index) should be selected. In this model the alternatives are a combination of conventional systems versus a proposed robotic system.

$$I = w_1 u(v_1) + w_2 u(v_2) + w_3 u(v_3) + w_4 u(v_4) + w_5 u(v_5) \quad (5)$$

in which  $I$  = robotization index or global utility;  $w_i$  = weight factor of  $i$ th variable,  $v_i$  = value of  $i$ th variable; and  $u$  = utility function. A positive value of  $I$  indicates that the operation should be carefully considered for the robotization.

The success of this model is directly related to the proper selection of the variables, accuracy of the utility curves and weight factors. If the decision criterion fall within separate disciplines of study then a professional in that area should be assigned to evaluate the measurement scale. In the assignment of weight factors the user must have a thorough knowledge of not only the operation tasks, but also the goals of the management. Overall the modeling of robotics for construction operations is necessary for the justification of implementation. The model enables the management to reduce the risks involved and consistently estimate the results of implementation. In the long run, this would aid in the increased use of robots throughout the industry.

#### IV. SUMMARY AND CONCLUSIONS

Seven major variables affecting on the feasibility of the robotics in construction industry were identified as: 1) cost effectiveness; 2) level of hazardous; 3) productivity; 4) quality improvement; 5) standardization of design and level of repetitiveness; 6) union resistance; and 7) technologically feasible.

Two models were developed for the robotics feasibility in the construction industry: 1) simplified management decision model; and 2) utility decision model. The ultimate output of these models provide an index which indicates the level of automation.

Hazardous construction operations are the prime motivation in the U.S. to implement robotics in the construction domain. However, the problem of lower productivity in construction industry is expected to be an incentive for future use of robotics. Developing new design techniques based on standard elements and repetitive operations must be further investigated. This can result in developing entirely new techniques of construction, feasible for the robotization.



## V. ACKNOWLEDGEMENTS

The efforts of graduate students in the Construction Management Program at Georgia Institute of Technology are the basis of this report. Appreciation is extended to H. Jones, S. Chawla, F. Nakad, A. Gutierrez, P. Fernandez, and C. Obetts.

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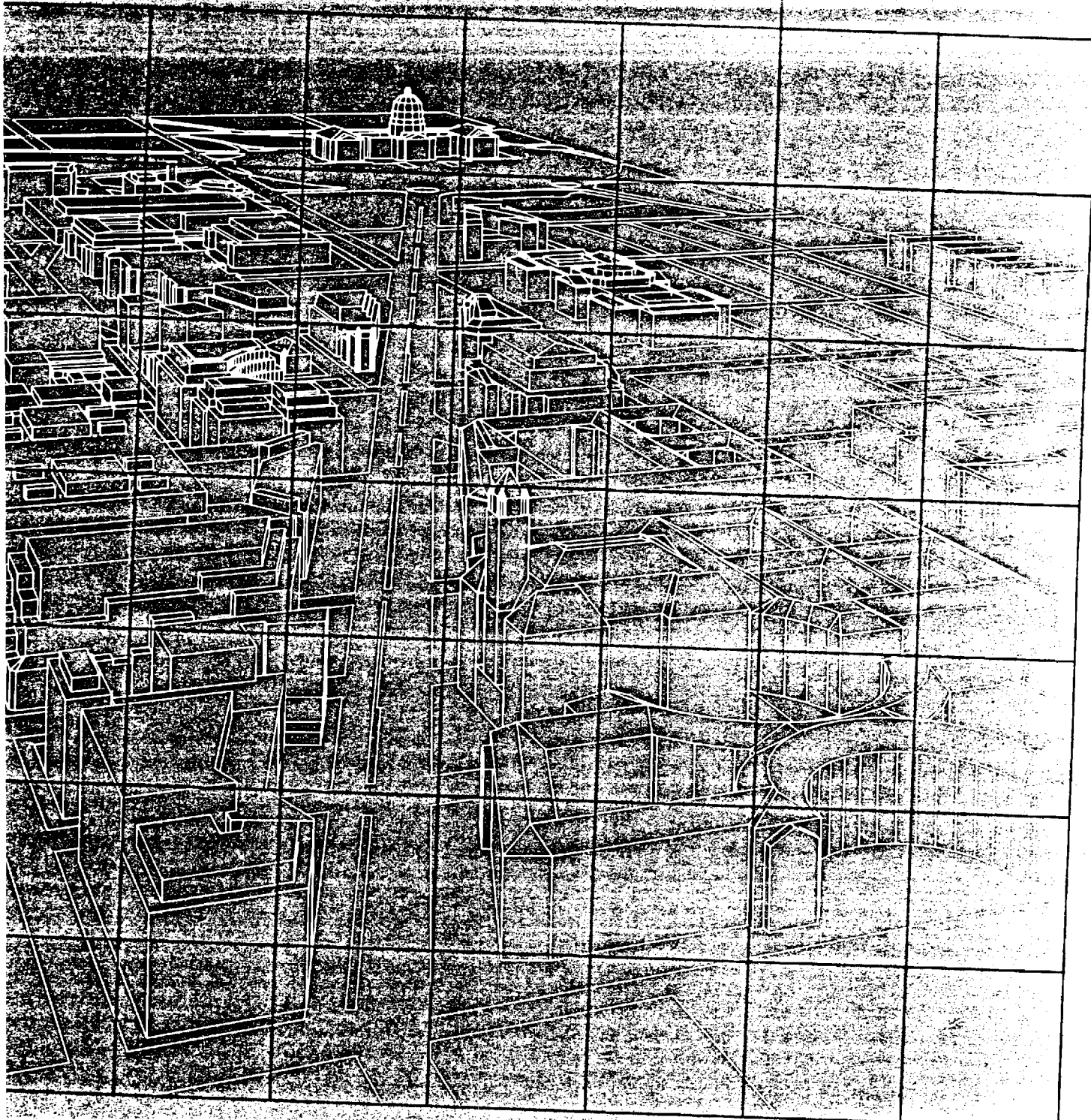
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# Socio-Economic Aspects of Robotization

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## KEYWORDS

Automation, Construction Industry, Feasibility Analysis, Robotics.

## ABSTRACT

Most major industries have passed through a period of intense industrialization. Some have reached a period of extensive automation to include the use of robots. In particular, the automotive industry has successfully used robots to enhance both production and improve quality control. Recent advancements in robotic technology, control systems, and computers have vastly broadened the applicability of robots. In the construction industry, robotics principles have been applied to certain construction machines. Such equipment as tunnel-boring machines, automated paving machines, and scrapers with computerized transmission controls have sensors and processing abilities that bring them within the realm of robotics. However, unlike the manufacturing sector, greater intelligence, load, and force range is needed for a construction robot. It is generally agreed that the major justification for using robots in construction operations is related to: 1) Improvement of worker safety and elimination of dangerous construction operations; 2) Increasing productivity; 3) Improvement of final quality. The objective of this paper is to explore the socio-economic aspects of the robotics feasibility in construction industry, and establish a basic foundation for the future research. In general, the following questions will be addressed. What are the economic benefits of robots? What are the impacts on labor? How can construction operations with high potentials for robotization be identified?

## Les aspects socio-économiques de la robotisation

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### MOTS CLEFS:

Automatisation, Industrie de construction, Analyse de faisabilité, Robotique.

### Sommaire:

La plupart des grandes industries ont traversé une période d'industrialisation intense. Certaines ont atteint un stade d'automatisation importante qui inclut l'utilisation de robots. L'industrie automobile, notamment, a utilisé des robots avec succès dans le but d'améliorer la production et le contrôle de la qualité. De récents progrès accomplis dans le domaine de la robotique, dans les systèmes de commande et dans l'informatique ont élargi le champs d'application des robots de façon considérable. Dans l'industrie de la construction, les principes de la robotique ont été appliqués à certains engins de construction. Des machines telles que les perceuses de tunnel, les répandeurs de revêtement automatisés et les aplanisseuses à commandes de transmission informatisées sont équipés de détecteurs, et ont des capacités de traitement telles, qu'il est possible de les considérer comme faisant partie de la famille des robots. Toutefois, dans le cas des robots de construction, les besoins en intelligence artificielle, en plage de charge et en plage de force sont plus importants que ceux rencontrés dans la fabrication. On s'accorde pour dire que les raisons suivantes justifient l'emploi de robots dans la construction: (1) l'amélioration de la sécurité des ouvriers et l'élimination des manoeuvres dangereuses inhérentes à la construction; (2) l'augmentation de la productivité; (3) l'amélioration de la qualité du produit fini. L'objectif de l'exposé ci-joint est d'explorer les divers aspects socio-économiques de la robotisation dans l'industrie de la construction et d'établir un fondement sur lequel se baseront les recherches futures. D'une façon générale, les questions suivantes seront traitées: Quels sont les avantages économiques des robots? Quel est leur impact sur la main d'oeuvre? Comment les opérations de construction étant le plus susceptible d'être robotisées peuvent-elles être identifiées?

## INTRODUCTION

Unlike the manufacturing industry, a construction site is a dynamic and random environment, therefore, a fully automated process requires a very intelligent control system, sophisticated sensors for feedback, an efficient material-handling system, and an advance mobility system. Under these conditions, it has become useful to explore at least those problems in the range of preliminary steps for the robotics feasibility in the construction industry.

Robots are used extensively by the manufacturing industry. However, the construction industry has unique characteristics which makes the robotization in most cases not a feasible alternative at the present time. It is not expected that robots will enter the construction trades before the end of next decade. The construction site is a random environment requiring a robot of highly sophisticated intelligence combined with a large load range and need for mobility. It seems that in the early days of robotics application in construction industry, the awareness of construction site hazards will provide the prime motivation to design and use a robot that would perform the tedious, repetitive, boring, dangerous and unpleasant construction jobs (Ref. 1).

Robot technology is not new, but many industries as construction are only just beginning to realize the impact that full automation could have in their production. Today, construction robots are still on the stage of research, and there are only few practical construction robots developed in the U.S., Japan, and some other countries. However, among all these robots only one or two may be called real construction robots and the rest are partially automated construction equipment (Ref. 2).

Although today there is differences of opinion about exactly what construction robot is, but in general may be defined as a fully automated mechanical device that can be programmed to perform construction tasks. In other words, robots are the machines which controlled by computers.

A further essential question is the determination of an economical practical level of automation for construction processes. It may be an optimum level of automation for each type of construction operation since excessive application of automation to a given operation may not be economical. In certain cases, partial automation may even lead to an increase in the unit price of construction and perform a feasibility analysis for each stage.

## SEQUENTIAL STAGES IN AUTOMATION:

To define an optimum level of automation for a given construction process, the following five basic classifications may be used: 1) Manual labor construction operation which is performed by hand, or packing; 2) Mechanized construction operation which is performed with tools, e.g., manual construction equipment, or with construction equipment.



operation. These are the construction machines which are controlled by human, e.g., drilling rock by a conventional drill, or excavation by a conventional loader. Most of the construction equipment at the present time are under this classification; 4) Partially automated construction equipment, or man-machine-computer operation. This stage of automation improves the conventional construction equipment by adding a partially automated control system to the actuators, e.g., laser leveling grader, automatic gear shifting scrapers, hydraulic excavator with bucket tilt control, or remote control construction equipment for the construction work in dangerous places; 5) Fully automated construction equipment (robot), or machine-computer operation, e.g., SSR-2 spray robot for fireproof spraying on steel structures (Ref. 3), developed by the Research Institute and Construction Machinery Division of Shimizue Construction Co. in Japan. In the U.S., the Civil Engineering and Construction Robotics Laboratory at Carnegie-Mellon University is heavily involved in research and development of the construction robots to perform tasks in environment that are unsafe for human. These robots require occasional human involvement.

How does a robot operate? Essentially the computer of robot is provided with information representing a model of the robot, with details of the environment, data relating to the tasks to be performed and with a number of planning algorithms. When in operation it continually receives information concerning the robot with internally sensed information, and the environment with externally sensed information. By using this information in conjunction with planning algorithms, which can refer back to past experience, the computer develops control over the robot, causing it to move towards the correct execution of the task assigned to it.

The main difference between a construction robot and a conventional construction equipment is that the robot is able to react with its environment without a human intervention. However, the publicity surrounding the introduction of robots into the construction field exaggerates the true state of the theoretical and practical knowledge of robotics. The technical challenge is considerable because, at present, the characteristics of robot are far from attaining the performance required in an unstructured and dynamic construction field.

Large construction companies with an interest on equipment automation have not given a great deal of attention to research in robotics. There are only a few international contractors who have introduced robotics into their field, however, these robots are not capable of detecting the complex information directed to them from the environment.

If the number of repetitive operations are very large and the output product is fixed, then it might be economical to implement a fixed automation plant. For example, if a prefabricated plant is planning to build a large (infinite) number of fixed construction products (e.g., prestressed concrete beams) which does not require any change in size or type of material, then a fixed automation may reach a lower unit price than a flexible automated plant. This is due to the large volume of production and a lower variable cost.

Considering these sequential stages, the objective of this paper is to describe the feasibility of the last stage (robotization) in relation with the other stages. In other words, what construction operations should be robotized.

## FEASIBILITY ANALYSIS

A modeling procedure is needed to evaluate the feasibility of robotics and justifying the implementation of robots in certain construction operations. In reality, robotics feasibility and justification is inter-disciplinary since it involves the input of several professional groups, therefore, this paper can only provide a guide for evaluation and discuss general considerations.

The following seven major variables affecting on the feasibility of the robotics are considered: 1) Cost Effectiveness and Economical Analysis; 2) Hazard Level; 3) Productivity; 4) Quality Improvement; 5) Standardization of Design and Level of Repetitiveness; 6) Union Resistance; 7) Technological Feasibility.

Any construction operation, if desired to be robotized, should satisfy a certain level of these variables. Since each construction operation is unique in nature, each operation will have different weight factors to the above variables depending on their level of importance in the operation. For example, in a welding operation inside a nuclear power plant with a high level of radiation, variables 2 and 7 will have higher weights than variable 5.

These variables must be analyzed in order to determine whether a particular operation should or should not be robotized. Next sections will describe briefly each of these variables.

### Cost Effectiveness and Economic Analysis:

Applying robotics to a particular construction operation will most likely involve a large initial capital investment. Capital investments are based on the evaluation of the spending requirements and the returns generated over the lifetime of the equipment. Sometimes a particular construction operation is technologically feasible but not financially. To determine whether a robot is economically feasible, costs and benefits should carefully be studied.

In general, a determination of the total investment required is necessary, then the effect of the investment on operation's expenses and profitability should be analyzed. Items to be considered as cash out-flows are: 1) Total robot cost (e.g., Robot, Accessories, Options, and Installation); 2) Maintenance cost (e.g., Spare Parts, and Maintenance); 3) Downtime cost; and 4) Increase in energy cost. Items to be considered as cash in-flows are: 1) Savings on labor costs; 2) Productivity and quality improvement; 3) Depreciation saving through tax; and 4) Salvage value. Current industrial robots have payback periods of 2-3 years when compared against direct labor.

## Hazard Level

Hazardous construction operations are very suitable for the robotization. The distinction between unsafe operations and hazardous operations should be made. Unsafe operations are assumed those in which there is a high occurrence of worker accidents. Accidents are considered to be the fault of the worker, either through carelessness or by the misuse of equipment. Hazardous operations are assumed those operations which expose the worker to an unhealthy environment (e.g., dust, radiation, heat, etc.). The worker is not considered responsible for the conditions but due to the nature of the operation, unhealthy human exposure is required. Historical data generally indicates the frequency of job related accidents, while standards relating to hazardous operations are provided by OSHA.

Some construction operations are hazardous, therefore, governmental and private agencies have dedicated special attention to this kind of operations. Several studies have been conducted in which permissible exposure limits for a variety of noxious elements commonly found in construction operations have been set. In determining if a particular operation is hazardous, the following areas should be investigated: 1) Concentration of dust; 2) Temperature levels; 3) Air and water pressures; 4) Noise; 5) Radiation, etc.

## Productivity

Productivity levels in a particular operation are indicators of the effectiveness of the different resources involved in the operation.

In order to determine if a particular operation is suitable for robotization from the point of view of productivity, it is necessary to set a desired or expected productivity level. After having conducted a detailed and precise study of the productivity variation according to the type of machine being utilized and according to the expected robot productivity variation, the decision-maker should be in the position to decide if the operation is suitable for robotization or not.

Generally, productivity of an operation is measured by dividing the total number of units produced by the total amount of resources utilized in a determined period of time.

Productivity can simply be defined as the ratio of output to input, typically given as units produced per man-hours required. A comparison between productivities of the current system and the proposed robotic system should be made. If historical data on productivity is not available then a study to determine these values must be made. Simulation of the operation's tasks and sub-tasks for both systems may be used to determine the value of productivity. Several assumptions may be needed to model the robotic system, especially if it is a new or unique application. The most desirable results would indicate that the robotic system provides greater productivity in the comparison (Ref. 4).

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If a construction operation is automated or robotized, it is expected to have a sharp increase in the productivity. The increased productivity, supposedly, gradually absorbs the cost incurred in the robot or automated equipment implementation. Obviously, productivity is not the only factor that pays for the robot. In some situations, the productivity achieved by a robotized operation remains the same, but substantial savings are expected to occur in other cost categories such as labor, overhead, etc., or even cost savings achieved by a better quality of the work.

A robot might have other uses in future projects. Therefore, the analysis must consider these possibilities, not just a study of whether or not the robot cost is justified by the better productivity achieved.

One must remember that certain construction operations involve considerable risk. In this situation, productivity plays a secondary role, because the main objective is to avoid detrimental and hazardous conditions. For these reasons, the project planner must weigh every factor accordingly to the desired goals.

#### Quality Improvement

One major reason for the implementation of robot is to produce a better quality compared to traditional systems. The results of quality analysis of the SSR-2 spray robot for fireproof cover work shows that the dispersion of the sprayed thickness decreased. Quality of a construction product can be measured by a numerical model which considers such characteristics as strength, dimension, color, etc. Only the relevant characteristics of an operation product should be considered. There is a direct correlation between cost and the level of quality improved.

#### Standardization of Design and Level of Repetitiveness

The cyclic and repetitive operations are the most suitable operations to be robotized or automated. A repetitive routine operation is a desirable operation characteristic for the robotization. A construction operation should be broken down into individual processes, tasks, and subtasks. The amount and type of repetition in each of these work divisions should be analyzed. The decision-maker determines the number of cyclic motions required in the production of one unit (Refs. 5 and 6).

Standardization of design also involves repetition but on a larger scale. Here, repetition is studied on the project or activity level. Basically, this parameter evaluates the number of production units required for successful robot implementation. Justification depends upon whether the number of production units fall within an optimum range. If not, perhaps some other man/machine system is more appropriate.

There are several means by which the number of production units in a project may be modified to fall within the optimum range for robotization. In the project planning phases it is advantageous to

orient various building components (i.e. steel framing, doors, windows, rooms, etc.) in a regular and predictable manner increasing the feasibility of robotization by increasing the quantity of repetitious work cycles. Standard dimensions, regular geometric shapes and standard size fixtures would simplify implementation. Simplifying the construction design would in turn simplify the robot's job, reduce the necessary 'learning period' (teaching and reprogramming) and thereby increase robot effectiveness.

Standard design and repetitive operation are two factors that are required for robotization or automation of any construction operation.

#### Union Resistance:

Labor unions currently have few standard policies concerning the automation or robotization of construction operations, therefore, the reaction from organized labor can only be estimated. Unions have traditionally viewed automation as providing improvements to working conditions and in most cases respond in a positive manner.

Union resistance is considered to be somewhat dependent upon the following: 1) number of workers being displaced; 2) union strength in the area; 3) policies of management (advance notice to union officials, placement programs for displaced workers, etc.). These parameters are more difficult to model because no definite measurement scale of union resistance exists.

#### Technological Feasibility

In spite of the technological advances achieved in the last few years, technology does not always provide the necessary elements to develop machines for certain kind of industrial operations. For this reason, it is important that this factor be analyzed in the first stages of the study in order to determine if technology provides the tools to develop the appropriate machine for the operation in question. If the study reveals that development of a robot is not technologically feasible, further study of the other factors are not necessary, since the whole operation cannot be achieved.

It is expected that mobile robots will find increased popularity in construction industry. A fixed robot has a limited sphere of operation and is not appropriate for the construction sites.

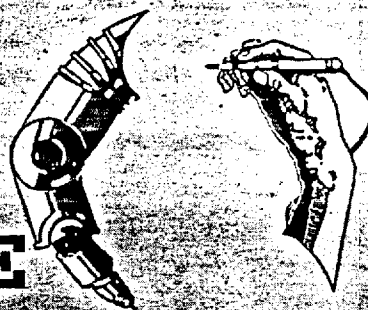
A construction wheeled vehicle robot, such as a motor car, with firmly inflated tires represents an ideal system with minimum energy to operate on smooth surfaces which have sufficient friction to the wheels to propel and steer the robot without slipping. Wheeled systems can only operate over relatively smooth surfaces. The track systems are the known alternatives to wheels for rough ground mobility.

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**Roozbeh KANGARI**

School of Civil Engineering

Georgia Institute of Technology

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**Major Factors in Robotization  
of Construction Operations**

## ABREGE:

La robotisation et l'automatisation de la construction d'un bâtiment nécessitent des méthodes techniques différentes de celles appliquées dans l'automatisation d'une usine. L'importance des opérations, leur mobilité, le genre de techniques utilisées et les conditions de travail ne sont pas les mêmes pour un chantier de construction et une usine. Une plus grande intelligence, une plage de charge et une plage de force plus importantes sont nécessaires pour un robot de construction. Les raisons principales pour lesquelles on utilise des robots dans la construction sont: l'amélioration de la sécurité des travailleurs et l'élimination de manoeuvres dangereuses; l'accroissement de la productivité et l'amélioration de la qualité du produit fini. Cet exposé présente une méthode d'étude systématique de la faisabilité de la robotique dans les manoeuvres de construction. Un système expert basé sur la connaissance et permettant aux entrepreneurs d'effectuer une étude préliminaire pour l'automatisation de la construction sera présenté. Ce modèle pourra servir de schéma pour évaluer les procédés de construction pouvant être automatisés.

## ABSTRACT

Robotization and automation of a construction process requires engineering approaches different from those that are applicable in factory automation. Construction site differs from industrial plant in scale of operation, mobility, type of processes and the work environment. A greater intelligence, load, and force range is needed for a construction robot. The main reasons for using robots in construction operations are: to improve safety of workers and eliminate dangerous operations; to increase productivity; and to improve final quality. This paper presents a systematic approach to study the feasibility of robotics in construction operations. A knowledge-based expert system is introduced which allows the contractors to perform preliminary study for the automation. The model can be used as a guideline in evaluating potential construction operations for the automation.

## INTRODUCTION

Although there still exist today differences of opinion about exactly what a robot is, there is a growing general consensus that robots will be increasingly adopted by construction industries throughout the world. Robot technology is not new, but many industries as construction are only just beginning to realize the impact that full automation could have in their production. Today, construction robots are still on the stage of research, and there are only few practical construction robots developed. However, among all these robots only one or two may be called real construction robots, and the rest are partially automated construction equipment (Paulson, 1985).

Robotization and automation of construction industry is an important step forward in the industry. For each construction process to be automated, it is necessary, on the basis of a detailed analysis, to determine the more important basic problems of automation and commence the solution of these problems by a systematic approach. With the wide-scale introduction of automation into industry, it is desirable, in the first stage, to do feasibility study for automation which is likely to give the best technical-economic effect. It is consequently of great importance to determine major factors affecting robotization which is rational from the socio-economic and technical viewpoints. The main objective of this paper is to identify major factors in robotization of construction operations, and to present a knowledge-based expert system for feasibility analysis.

## MAJOR FACTORS IN ROBOTIZATION

A knowledge-based expert system modeling procedure is implemented to analyze the feasibility of robotics in construction operations. The following seven major variables are considered: Level of Repetitiveness; Cost Effectiveness; Technological Feasibility; Productivity Improvement; Level of Hazard; Union Resistance; Quality Improvement.

A repetitive routine operation is a desirable operation characteristic for the robotization. The amount and type of repetition in each of these work divisions should be analyzed. Relationship between number of units produced by robot and total cost can be shown as Figure 1. The total cost is divided into fixed and variable costs as shown in Equation 1.

$$(\text{Total Cost of Robot}) = a(\text{Number of Units Produced}) + b \quad (1)$$

in which  $a$  = variable cost; and  $b$  = fixed cost. If Equation 1 is divided by "Number of Units Produced", then Equation 2 can be shown as:

$$\frac{\text{Total Cost}}{\text{Number of Units}} = a + \frac{b}{\text{Number of Units}} \quad (2)$$

This equation can be shown graphically as Figure 2. Similar curves can be developed for conventional construction equipment, and fixed automation. These curves are presented in Figure 3. This figure shows the relation between unit cost and number of units produced. The intersection points

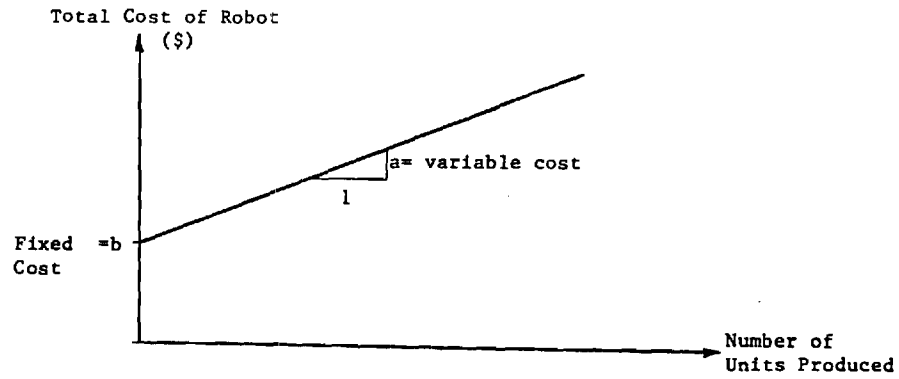


Figure 1. Total Cost Analysis

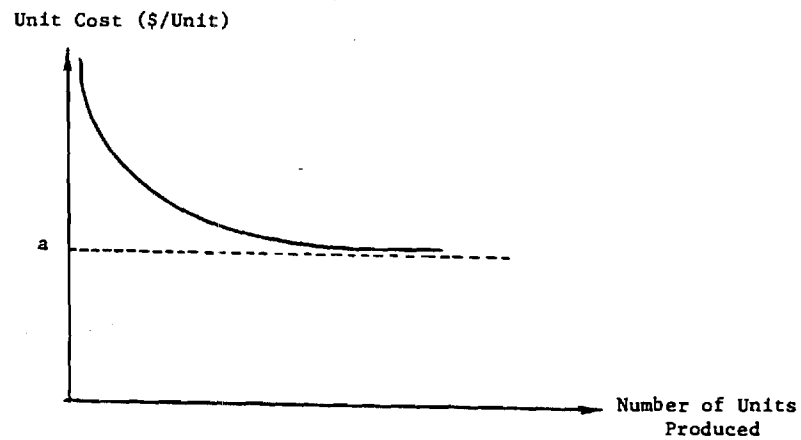


Figure 2. Unit Cost Analysis

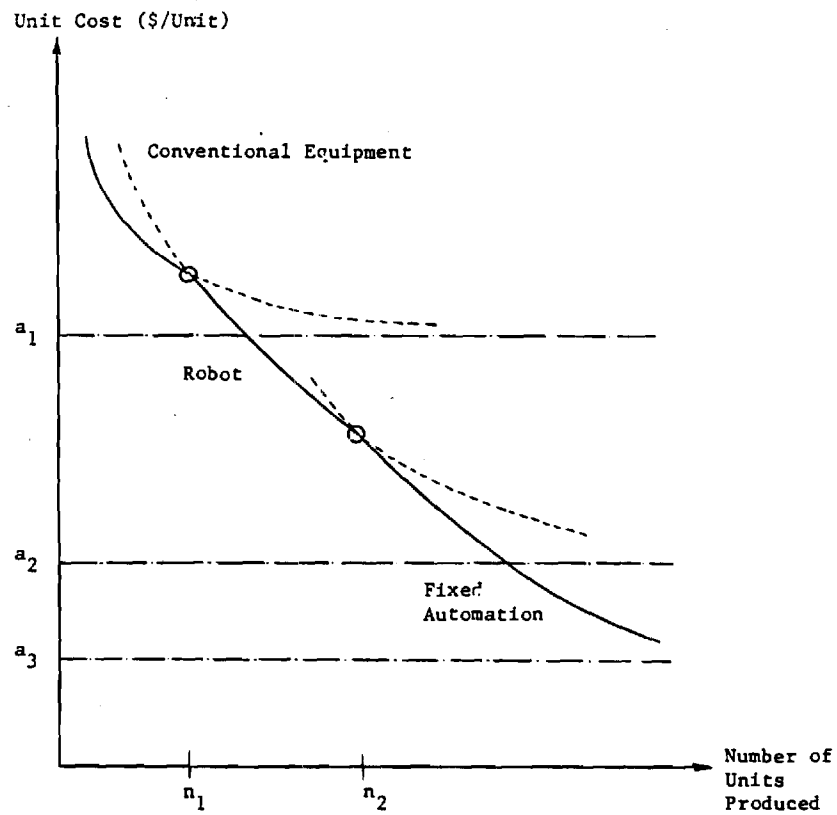


Figure 3. Evaluating Optimum Number of Units

( $n_1$ ,  $n_2$ ) show that operation should change from conventional equipment to robot or fixed automation.

Standardization of design also involves repetition but on a larger scale. Here, repetition is studied on the project or activity level. Basically, this parameter evaluates the number of production units required for successful robot implementation. Justification depends upon whether the number of production units fall within an optimum range. If not, perhaps some other man/machine system is more appropriate (Halpin, 1976).

To estimate the cost effectiveness of a robot operation; a determination of the total investment required is necessary, then the effect of the investment on operation's expenses and profitability should be analyzed. Items to be considered as cash out-flows are: 1) Total robot cost (e.g., Robot, Accessories, Options, and Installation); 2) Maintenance cost (e.g., Spare Parts, and Maintenance); 3) Downtime cost; and 4) Increase in energy cost. Items to be considered as cash in-flows are: 1) Savings on labor costs; 2) Productivity and quality improvement; 3) Depreciation saving through tax; and 4) Salvage value. Current industrial robots have payback periods of 2-3 years when compared against direct labor.

Another major factor to consider is that technology does not always provide the necessary elements to develop machines for certain kind of industrial operations. Therefore, it is important that the necessary sensor systems, motors, manipulators, control systems, mobile systems, be analyzed in order to determine if technology provides the tools to develop the appropriate machine for the operation in question. If the study reveals that development of a robot is not technologically feasible, further study of the other factors are not necessary.

If a construction operation is automated or robotized, it is expected to have a sharp increase in the productivity. The increased productivity, supposedly, gradually absorbs the cost incurred in the robot or automated equipment implementation. Obviously, productivity is not the only factor that pays for the robot. In some situations, the productivity achieved by a robotized operation remains the same, but substantial savings are expected to occur in other cost categories such as labor, overhead, etc., or even cost savings achieved by a better quality of the work. Certain construction operations involve considerable risk. In this situation, productivity plays a secondary role, because the main objective is to avoid detrimental and hazardous conditions. For these reasons, the project planner must weigh every factor accordingly to the desired goals (Sangrey, 1984).

Unsafe and hazardous construction operations are usually suitable for the robotization. Hazardous operations are those operations which expose the workers to an unhealthy environment. It is necessary to develop an evaluation procedure that relates hazardous work tasks in the construction industry to the automated remote control/robot systems. Research is conducted at Georgia Tech: 1) to identify major hazardous construction work tasks; 2) to identify important hazardous factors involved in the applicable work tasks; 3) to evaluate the hazard, by using special instruments and permissible exposure limits; 4) to develop a series of work task diagrams in which all the work conditions are considered; and 5) to

develop a rationale for replacing the worker in the hazardous environment, with a controlled remote equipment or a robot. Figure 4 shows a general spray painting work task. In this work task the application of different kinds of paint, with different solvents and additives, can create a possible hazard to the worker. From this figure, it can be determined when and where this hazard can occur, and if it is suitable to replace the workers by a robot.

At this time, the construction labor organizations are nominally interested in the potential use of robotics in the construction industry. This is fostered by the belief that the construction environment is too random and demanding to allow robots to function effectively for the foreseeable future. Thus, no formal policy has been developed towards robotization, and the cavalier statement that "the unions will not stand in the way of progress or the new technology to achieve this progress" can be made easily. However, the labor organizations need look no further than the recent experiences of the automobile and steel industry labor unions to achieve the needed hindsight with regard to what happens to labor when a shortsighted approach is taken toward robotic applications. Union resistance is considered to be somewhat dependent upon the following: number of workers being displaced; union strength in the area; policies of management (advance notice to union officials, placement programs for displaced workers, etc.). These parameters are more difficult to model because no definite measurement scale of union resistance exists.

Quality improvement is an important factor in developing robots. Generally, robot produces better quality than traditional systems. Quality can be measured by such characteristics as strength, dimension, color, and etc. Relationship between cost and the level of quality improved must be carefully analyzed by contractors.

#### KNOWLEDGE BASED FEASIBILITY ANALYSIS OF ROBOTIZATION

A model for robotics feasibility analysis in construction industry based on knowledge-based expert system was developed. Figure 5 shows an inference net for the developed model. The system considers the above seven important factors for its analysis. A microcomputer expert system shell program was implemented. Information is presented by production rules with many explanation modules (Kangari, 1985).

The model has utilized a confidence level for the analysis of the degree of repetitiveness. The economical analysis part consists of: 1) whether robotization is commercially economical; and 2) if it is economical to do research and build a new robot.

The final result of this model is a set of recommendations about a given construction operation which describes whether it should be robotized. A confidence level is associated with each outcome. The necessary suggestions to improve or further automate a construction process is provided. The model is designed to quantify qualitative judgements on the part of an expert group, and to combine that with the results of algorithmic model which estimates costs and production.

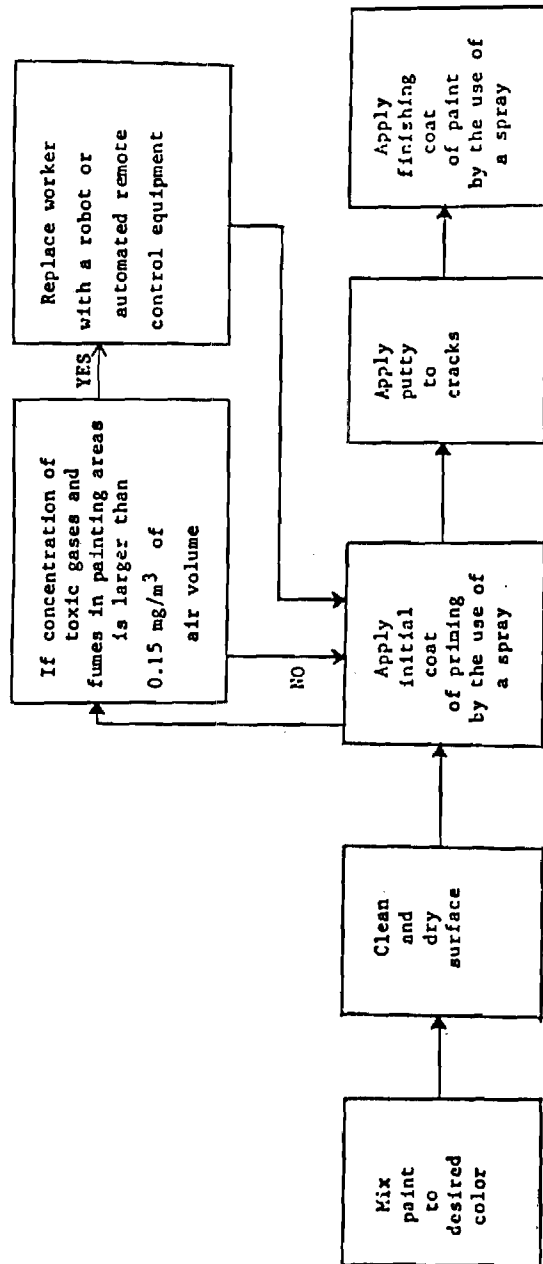


Figure 4. General Spray Painting Work Task Diagram



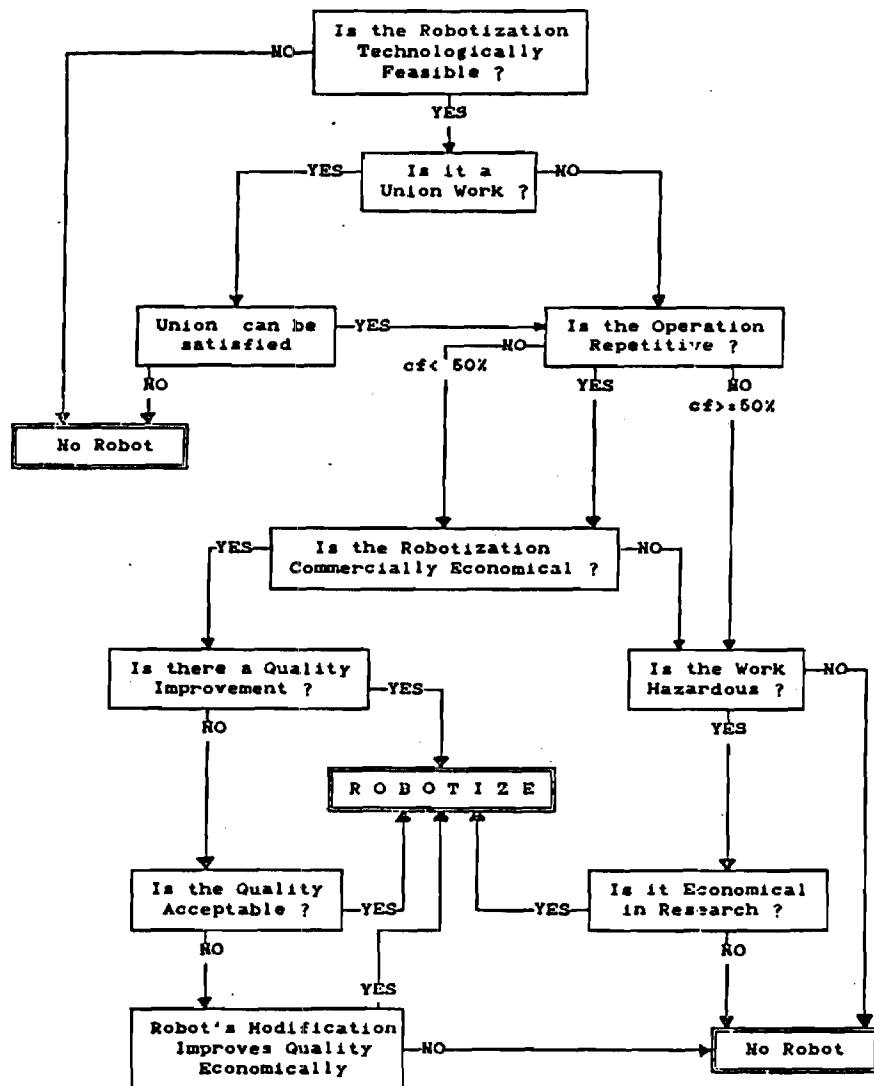


Figure 5. Knowledge Based Expert System Inference Net for Feasibility Analysis of Robotics in Construction

## SUMMARY AND CONCLUSIONS

A knowledge-based expert system was developed to do preliminary analysis of feasibility of the robotics in construction industry. Major factors were: level of repetitiveness; cost effectiveness; technological feasibility; productivity improvement; level of hazard; union resistance; and quality improvement. The model implements the knowledge collected from research workshops conducted at Georgia Tech with professionals to discuss potential construction operations for robotization. The final result of this model is a set of recommendations about a given construction process which describes whether it should be robotized. Developing new design techniques based on standard elements and repetitive operations must be further investigated. This can result in developing entirely new techniques of construction, feasible for the robotization.

## ACKNOWLEDGEMENT

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